WIDE BAND PERFORMANCE OF LOW LEVEL TRAVELING-WAVE AMPLIFIERS

STANLEY T. COUNTS

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Stanley T. Counts

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by

Stanley Thomas Counts

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1 9 5 5

This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

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PREFACE

This thesis is intended to familiarize the reader with the wide band characteristics of traveling-wave amplifiers. The scope is limited to low level traveling-wave amplifiers employing helix slow wave structure. An elementary qualitative theory is presented. The effects of secondary emission on noise figure and traveling-wave tube stability are discussed.

The experimental work for this paper was performed at Sylvania Electric Products, Inc., Microwave Tube Laboratory, Mountain View, California. The writer is indebted to Paul G. Bohlke, Donald S. Scarborough, and William Thon of Sylvania for their assistance and cooperation. Appreciation is also expressed to Dr. W. M. Bauer of the U.S. Naval Post-graduate School for his assistance and guidance. And finally, I am indebted to my wife, Bettejan, who assisted in the preparation of the manuscript and in other less tangible ways.

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CHAPTER I

INTRODUCTION

1. General

The traveling-wave tube is a special type of vacuum tube used in the microwave frequency range. This type of tube has been in existance for little more than a decade and must be considered as being in its infancy from the standpoint of both development and application. In comparison to other microwave devices, such as klystons and magnetrons, the primary advantage of traveling-wave tubes is the tremendous bandwidth over which these tubes will operate. A traveling-wave amplifier is capable of giving considerable amplification over an octave at frequencies from approximately 200 megacycles to a present day practical limit of fifteen kilomegacycles. Above fifteen kilomegacycles it is not now practical to use such large bandwidths as an octave would be. As an illustration of what such a bandwidth means, the entries in Webster's Unabridged Dictionary could be sent in Morse code in one-sixteenth of a second using a present day traveling-wave tube [6]. The disadvantages of traveling-wave tubes can to some extent be associated with the fact that they are still undergoing development. Some of these are the number of power supplies required, the space required for the tube and associated circuitry, and the difficulty in adapting these tubes to quantity production with uniform quality.

2. Histroical background.

The traveling-wave tube grew out of the efforts of Rudolph Kompfner [7] [8], with its conception occurring in 1942. Kompfner was seeking to overcome the limitations of the klystron when used as a high sensitivity amplifier in the microwave region. The main objection to the klystron was the transit time effects of the electrons crossing the buncher and catcher grids. In trying to overcome the transit time effects the traveling-wave tube was born. Kompfner's idea was to have the electric field and the electron stream travel at the same velocity so that optimum energy transfer would be obtained, both in the original bunching of the beam and in the extraction of energy at the output of the device.

From this idea, Kompfner devised a "slow wave" structure, consisting of a coaxial line with the center conductor a helix. When an electron stream was shot down the center of the helix, with a velocity near to the axial velocity of the wave on the helix, amplification occurred as a result of the interaction of the field wave and the electron stream. All present day traveling-wave tubes are based upon this principle.

3. Scope of presentation.

The scope of this paper will be limited to low level, wide band traveling-wave amplifiers using helical slow wave structures. The experimental work was performed on traveling-wave amplifiers with a designed frequency range of 2000 to 4000 megacycles and a power output of from 15 to 100 milliwatts.

CHAPTER II

GENERAL DESCRIPTION OF LOW LEVEL TRAVELLING-WAVE AMPLIFIERS

A typical traveling-wave amplifier consists of an electron gun, with cathode, control electrode, and anode; the helical slow wave structure; and collector in an evacuated glass envelope. External to the envelope will be input and output coupling devices and an attenuator. In addition to the above will be a magnetic field for focusing the electron beam and associated power supplies.

The electron guns are usually designed for either parallel flow or convergent flow depending upon the value of magnetic field to be used and whether the amplifier is dispersive or non-dispersive. A dispersive amplifier is a voltage tunable amplifier and a non-dispersive amplifier operates with constant helix voltage over a wide frequency range.

In wide band amplifiers the helix is generally wound with a uniform number of turns per inch and with a constant radius in order to simplify manufacture and to take advantage of the broad band properties of such a helix.

The purpose of the collector is to collect the electrons in the beam after they have passed the interaction region. The collector geometry and material from which it is made will influence noise figure and tube stability. This last statement will be discussed later.

The input and output coupling devices are for the purpose

of introducing and extracting r.f. energy onto and off of the helix. They may be cavities, waveguide sections, antennas, helical couplers, etc. The helical coupler is in wide use today at frequencies below ten kilomegacycles.

The attenuator has a threefold purpose: (1) to prevent regeneration by attenuating reflections caused by imperfect coupling devices, (2) to provide isolation between input and output circuits, and (3) to attenuate the backward modes. The attenuator takes various forms such as aquadag sprayed on the glass envelope, iron plating of the helix itself, coupled helices, etc.

The magnetic field may be provided by long solenoids or by permanent magnets if the magnets will give the proper shape and amount of field. Solenoids are usually used at the present state of the art.

CHAPTER III

QUALITATIVE THEORY OF TRAVELING-WAVE AMPLIFIERS

1. State of present theoretical development.

The complete theory of the traveling-wave tube is extremely complex and at the present writing has not been mathematically formulated. A great deal of effort has been expended along this line. Several authorities, Pierce [14], Field [13], Kompfner [9], and others have derived small signal theories that are all in general agreement. Nordsieck [11] and Tien [18] have attempted to formulate a more complete theory with good results, but the work involved in solving the non-linear differential equations was staggering. It may be possible to publish a complete theory at a later date when more is known of the solutions of non-linear differential equations.

The interaction phenomena is comprehended at least qualitatively. Dunn [4], in an unpublished paper, has proposed a qualitative explanation of the interaction phenomena and the reason amplification occurs. The following presentation will be essentially the theory Dunn presented.

2. Presentation of theory.

The simplest form of a traveling-wave amplifier will contain a slow wave structure (typically a helix), and an electron beam passing near to the slow wave structure. Figure 1 shows such a configuration. The velocity of the

electron beam will be very close to the phase velocity of the helix. The r.f. wave impressed on the slow wave structure has a component of electric field parallel to the motion of the electrons. It is by means of continuous interaction, between the electric field component parallel to the electron beam and the beam itself, that amplification occurs.

For the first step in the development of the theory assume (1) that space charge effects are negligible and (2) that a constant amplitude field wave and a uniform electron beam are being propagated in the same direction with the same velocity. With reference to figure 2, the forces on the electrons due to the applied field wave will be such to form a condensation of electrons at points C and D and a rarefaction of electrons at points A and B. In other words the electron beam will become bunched. The greater the time the beam and field wave travel together the denser the bunches of electrons become. Pierce and Shepherd have shown that the alternating current due to the passage of bunches of electrons past a stationary reference is proportional to the square of the time the field has acted on the electrons(See Appendix A). This statement also means that the charge density of the bunches increases as the distance squared (shown in figure 3).

If no other action took place, the bunches would reach maximum density then would debunch and the electrons would return to the original unbunched condition. The process

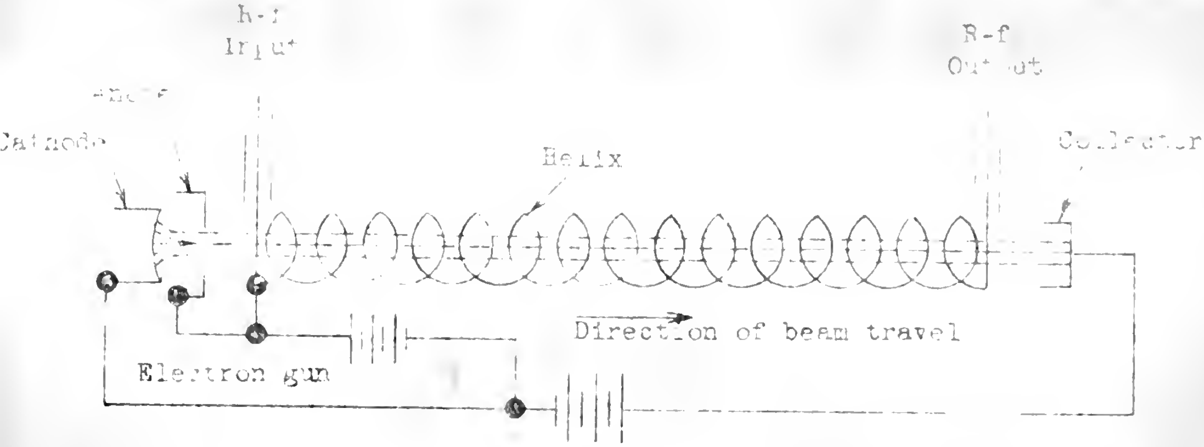
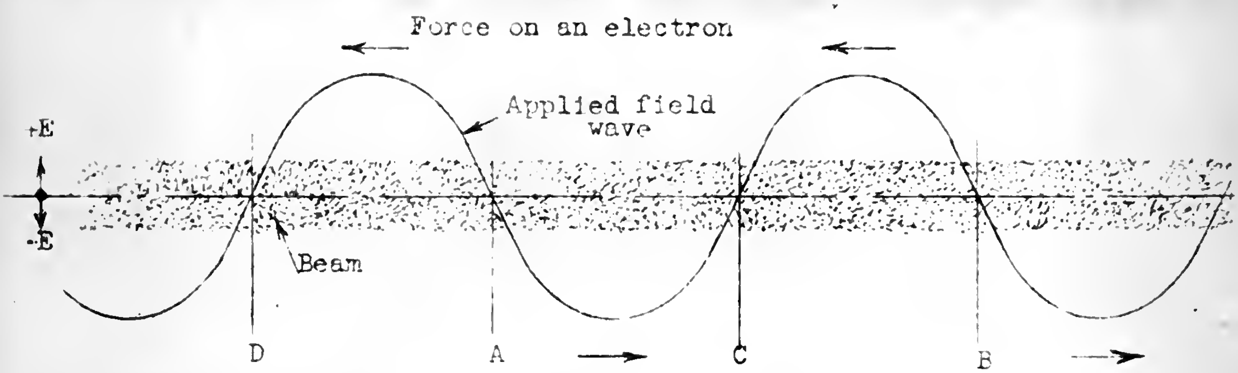
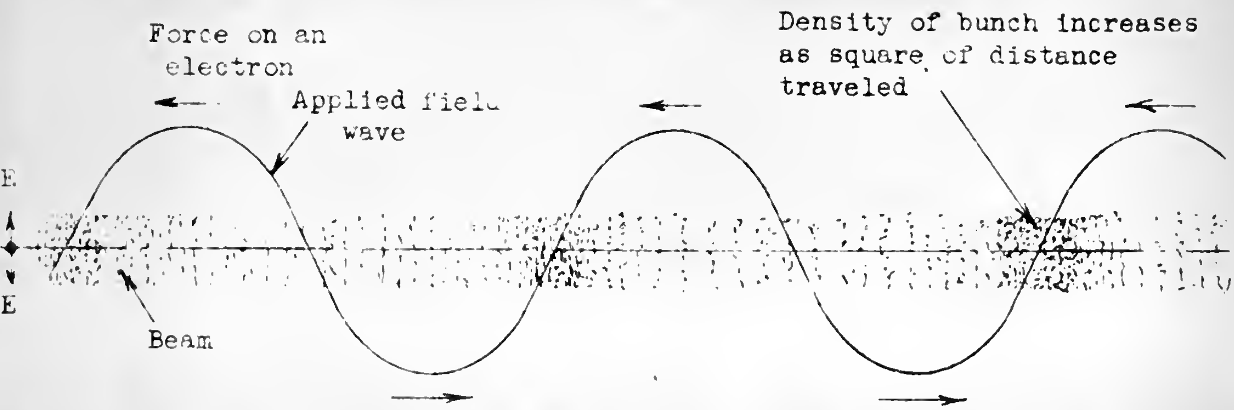


Figure 1



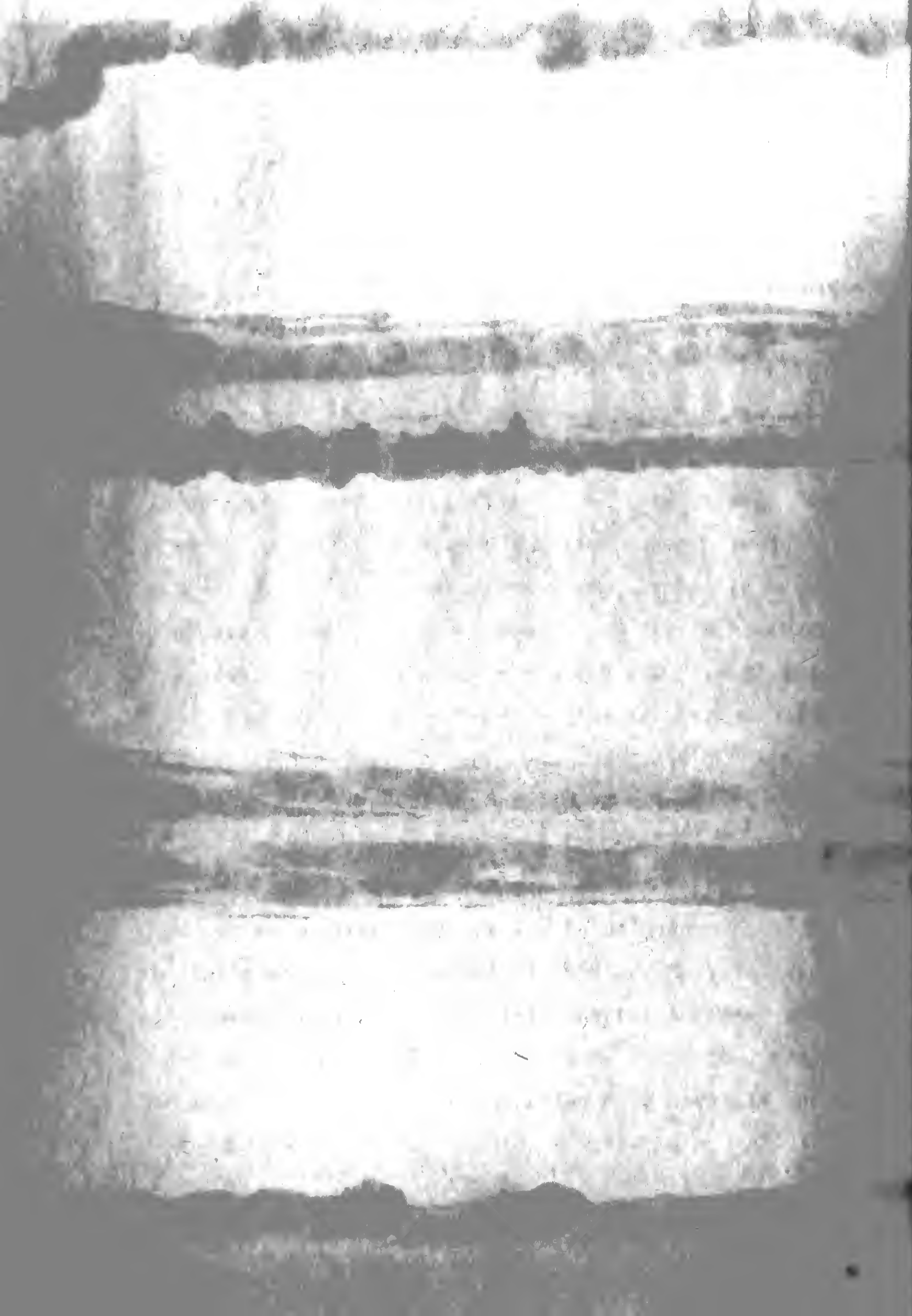
Direction of wave and beam travel

Figure 2



Direction of wave and beam travel

Figure 3



would then repeat. In the traveling-wave tubes being considered, the interaction phenomena prevents the maximum bunching condition from being reached. A bunched beam traveling past a slow wave structure will induce a field wave on the structure by a form of transformer action (Appendix B).

As the second step in the development consider the beam divided into incremental elements of alternating current with each increment inducing a minute field wave at the nearest point of the slow wave structure, refer to figure 4. Each current element will induce a field wave that consists of two components, one traveling toward the gun, the other toward the collector. These component waves will have equal magnitudes and will be in phase with the current element inducing them. This process results in a total field wave traveling toward the collector and a total field wave traveling toward the electron gun. The wave traveling toward the collector is the sum of all the infinitesimal waves traveling in that direction and similarly for the wave traveling toward the gun.

With the velocity of the electron beam equal to the phase velocity of the circuit (slow wave structure) all of the infinitesimal induced field waves traveling toward the collector will be in phase and will add. The assumption that the electron beam velocity and the phase velocity of the circuit are equal is a valid one. In an actual tube

they are very nearly equal with the beam velocity being slightly the larger.

For the induced field waves traveling toward the gun, consider two elements dE_1 and dE_2, separated by a quarter wave length on the circuit as shown in figure 4. The current increment dI_2 in moving from z_1 to z_2 advances ninety degrees in phase. The induced field wave dE_2 traveling toward the gun from z_2 to z_1 also advances ninety degrees in phase. Thus, by the time dI_1 arrives at z_1 the two field waves dE_1 and dE_2 traveling toward the gun are in phase opposition and cancellation occurs. Cancellation would be complete if dE_1 were the same magnitude as dE_2. However, dE_2 is greater than dE_1 as the exciting current is growing as distance squared. The increase in exciting current per quarter wave-length will be small and the magnitudes of the field waves dE_2 and dE_1 traveling in the negative z direction will differ only by a small amount. The end result will be only a small total field wave traveling toward the gun. Further, this wave will not be amplified as its velocity relative to the beam velocity is much higher than that required for synchronism. This wave is considered negligible in comparison to the wave traveling toward the collector in subsequent development.

The present development is (1) the originally applied r.f. field wave produced a bunched electron beam. The bunches produced will lag the applied field wave by ninety

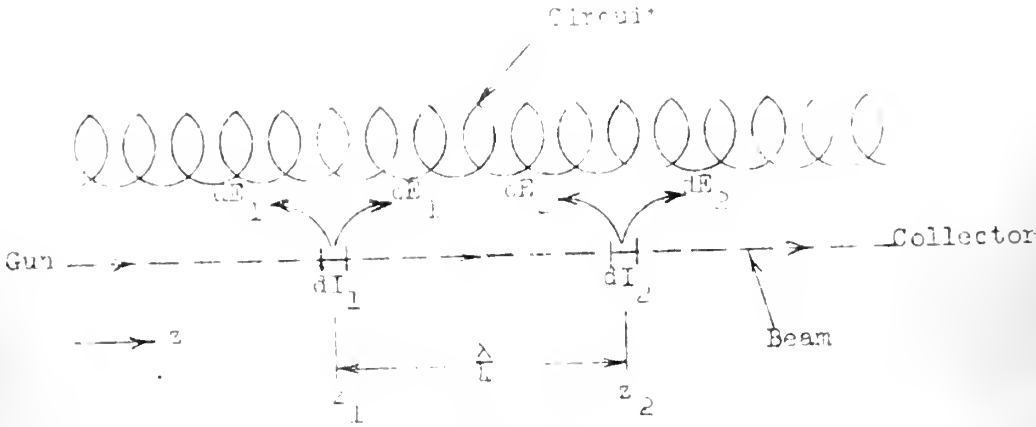


Figure 4

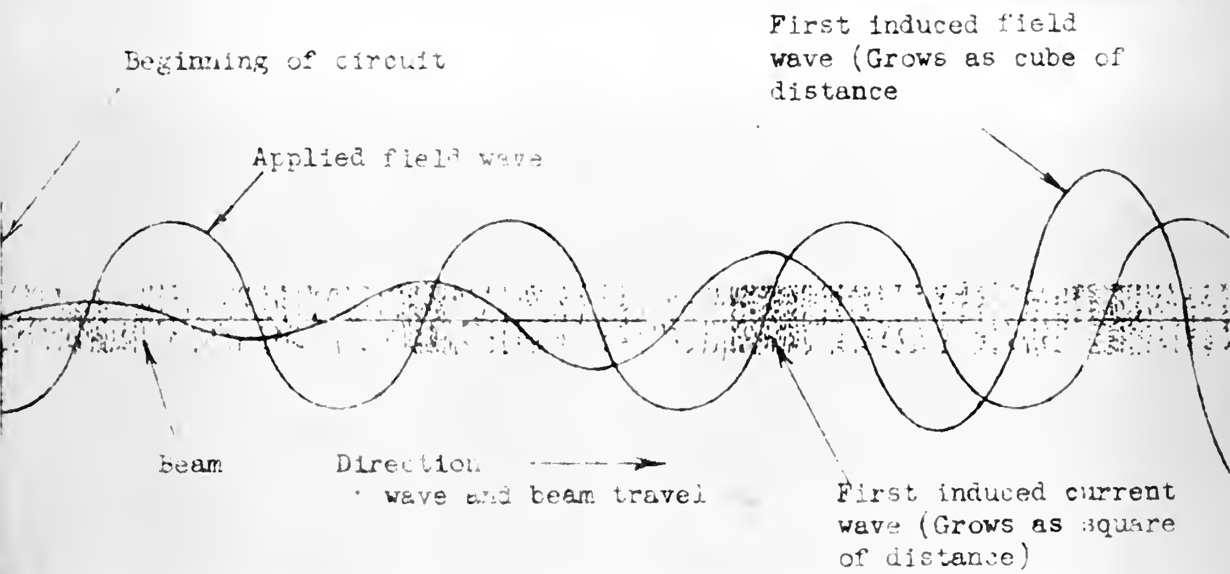


Figure 5

degrees. The bunched beam induces field waves onto the circuit. These field waves are in phase with the inducing current.

The next logical step is to postulate these induced field waves also contribute to a second bunching process just as the originally applied field wave did. These secondary bunches will increase as the fifth power of distance, however, and will be ninety degrees out of phase with the initial induced field waves and hence with the original bunches. This can be shown as follows:

Let

E = the original applied wave

$I(z)$ = current induced by the applied wave

$E'(z)$ = the wave induced by $I(z)$

$I(z) = I_o z^2$ (see Appendix A)

The wave induced by $I(z)$ will grow as:

$$E'(z) = \int_0^z K I_o z^2 \, dz$$

$$E'(z) = \frac{K I_o z^3}{3} = E_o' z^3$$

Thus, the field wave induced as a result of the initial bunching process grows as distance cubed (see figure 5). This total induced field wave grows faster than the exciting current due to the addition of small in phase components. For the secondary bunching process again refer to appendix A and replace $E(\xi)$ by $E_o' z^3$ in the equation for $\dot{\eta}(z)$. The result of this is to obtain a secondary current due to the induced field waves that grows as the fifth power of distance.

The process repeats with the secondary bunches inducing a field wave that increases as the sixth power of distance, etc. The total field wave that results from the original applied wave and each of these interaction phenomena will consist of component waves whose amplitudes increase as z^0, z^3, z^6, z^9, z^{12}, etc. Kompfner [7] obtained the expression for the total wave in closed form. This is shown in appendix C. The form obtained is for an exponential increase, and thus we see qualitatively that this should be the general form of increase of the field in traveling-wave amplifiers.

Also, the preceeding analysis gives an indication of how the beam transfers energy to the circuit. Under the assumption of no space charge effects there is no net energy required to bunch the beam. There are as many electrons slowed down as are speeded up in order to form the bunches with the result that the energy content of the beam is unchanged. However, in setting up the fields on the circuit there is a transfer of energy from the beam to the circuit. When viewed from the total wave (the original applied wave plus all of the induced waves) the energy transfer process is as follows: The total field wave is traveling slower than the beam since it is composed of the induced wave components of which each induced wave lags the previous one by ninety degrees. Thus, energy is ultimately transferred from an electron beam to a wave that is traveling slower than the beam. Pierce and Field [13] have shown that this is essential in order to produce a growing wave.

CHAPTER IV

TYPICAL PERFORMANCE CHARACTERISTICS OF THE LOW LEVEL TRAVELING-WAVE AMPLIFIER

1. Characteristics of traveling-wave amplifier R.E.T.M.A. number 6493.

As mentioned in chapter I the experimental work was performed with low level wide band traveling-wave amplifier. The particular tube used was the R.E.T.M.A. type 6493. The 6493 traveling-wave tube employs a helical type wave propagating structure with a designed amplification bandwidth of from two to four kilomegacycles. The maximum power output is 15 milliwatts or greater. The tube is convection cooled. It is designed for c.w. and/or pulsed operation working into a 50 ohm coaxial line. The focusing is accomplished by a uniform magnetic field, normally provided by a solenoid. A photograph of the 6493 traveling-wave tube is shown in figure 6. The R.E.T.M.A. characteristics are given in Appendix D. In addition to the R.E.T.M.A. characteristics the following information is given. The mean diameter of of the helix is.105 inches. The helix is made of tungsten wire, partially iron plated, .008 inches in diameter. The active helix length is nine inches wound uniformly with 64 turns per inch. A nonex glass envelope .115 inches inside diameter and .175 inches outside diameter surrounds the helix. At the present time the glass envelope is pinched at either

end of the helix in order to keep the helix reasonably rigid. The glass wall thickness is a critical parameter in the design of these tubes as it influences the amount of dielectric loading and hence the phase velocity of the helix. As a general rule, the thinner the glass envelope, the better the tube performance.

2. Purpose of experimental tests.

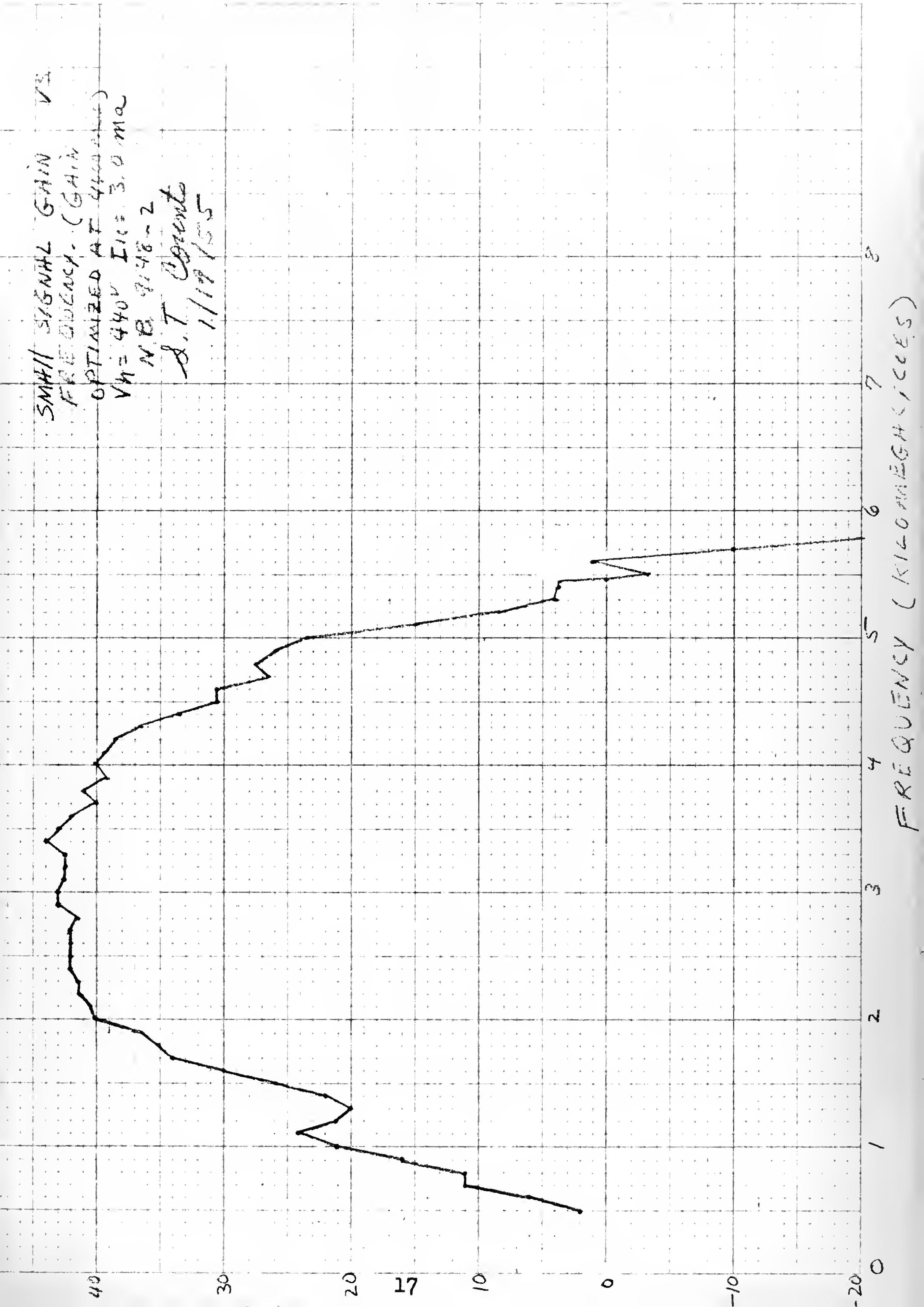
The experimental work performed concerned testing a low level, wide band, traveling-wave amplifier over wide a frequency range as possible to determine its behavior and characteristics outside as well as inside the designed bandwidth. A series of measurements were performed on these tubes to determine the above mentioned characteristics. Every effort was made to obtain similar tube operating conditions from day to day. Except where otherwise explained the tube was operated in the manner of its most probable use. The usual operating procedure for this type of traveling-wave amplifier (after setting the focusing field and beam current to the rated values) is to optimize the tube for maximum stable small signal gain at the high end of the designed band, i.e. at 4000 megacycles. This procedure usually gives optimum wide band amplifier performance in the designed frequency range.

3. Small signal gain.

Figure 10 shows a schematic diagram of the equipment used to measure small signal gain. The technique used was

a difference technique. The difference between the attenuator readings when the tube is switched in and out of the circuit for the same signal height on the cathode ray oscilloscope is the small signal gain at the frequency setting of the signal generator. This method is accurate to within one-half of a decibel when the attenuator has been properly calibrated. Figure 7 shows a typical plot of small signal gain versus frequency. This figure shows the tremendous bandwidth available in traveling-wave tubes. The bandwidth could be broadened even more if the coupling devices were to be improved [9]. Another graph (figure 8) shows the variation of small signal gain as the helix voltage is changed for maximum gain at each frequency. The violent fluctuations in gain at the higher frequencies and due to varying impedance matches of the input and output couplers. At frequencies where the couplers are efficient there is a gain peak, etc. Also shown on figure 8 is a plot of synchronous helix voltage (helix voltage that gives maximum gain). The curve shows the synchronous voltage to be relatively constant at frequencies above 2000 megacycles. At frequencies below 2000 megacycles the amplifier is dispersive, an inherent property of the helix type slow wave structure. In the dispersive region the amplifier must be voltage tuned to realize a reasonable amount of gain. With the couplers matched properly in the dispersive region this type of tube can be used quite efficiently as a voltage tuned amplifier.

Figure 7


SMALL SIGNAL GAIN VS
FREQUENCY. (GAIN
OPTIMIZED AT
Va = 440v Ic = 3.0 ma
NB 9148-2
1/19/55
FREQUENCY (KILOMEGACYCLES)
0
1
2
3
4
5
6
7
8
40
30
20
10
0
-10
-20


SMALL SIGNAL GAIN VS FREQUENCY
SYNCHRONOUS HELIX VOLTAGE VS FREQUENCY
NOTE BOOK 9148-11
A.T. Counts
2/11/55
I_K = 3.0 ma
FREQUENCY (KMCS)
0
1
2
3
4
5
6
7
8
-20
-10
0
10
20
30
40

The small signal gain curve will show a fine grain structure of gain variation if the frequency is swept (figure 9, a & b). Not all of the variations are due to the tube, some are due to the coaxial cables used in the input and output circuits, however, they are predominately due to the tube itself. These small variations can be reduced by using direct current on the filaments instead of the usual alternating current. This figure also shows the difficulty in obtaining a flat gain curve as the maximum gain is increased. Figure 9(a) shows pronounced peaks with a maximum gain of 48 db. At 36dbmaximum gain (figure 9(b) the overall gain curve is much broader and there are fewer peaks.

4. Impedance matching.

The impedance match between input and output coupling devices and the helix is one of the most important factors in determining how well the tube will operate. The input and output coupling devices on the tubes tested were of the coupled helix type. A helical coupler is a short length of helix wound in the opposite sense to the main helix with its phase velocity such that it follows the same variation with frequency as does the phase velocity of the main helix. In actual practice the phase velocity of the helical couplers can be made to follow the phase velocity of the main helix quite closely. This is done by optimum design of coupler diameter and turns per inch. The diameter of the helical coupler can be allowed to vary only a very small amount as

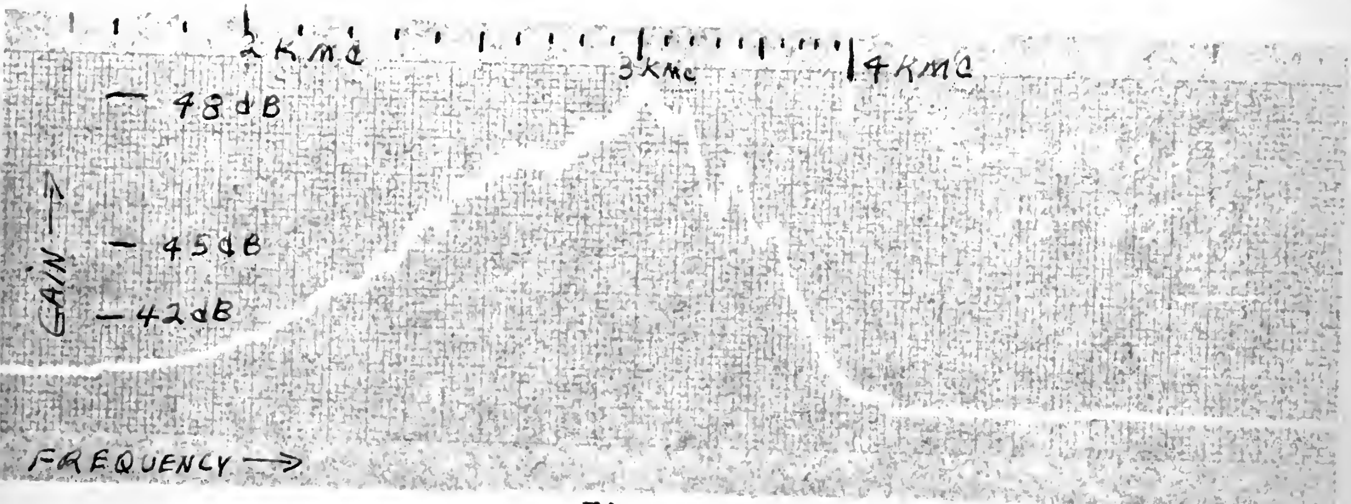


Figure 9a

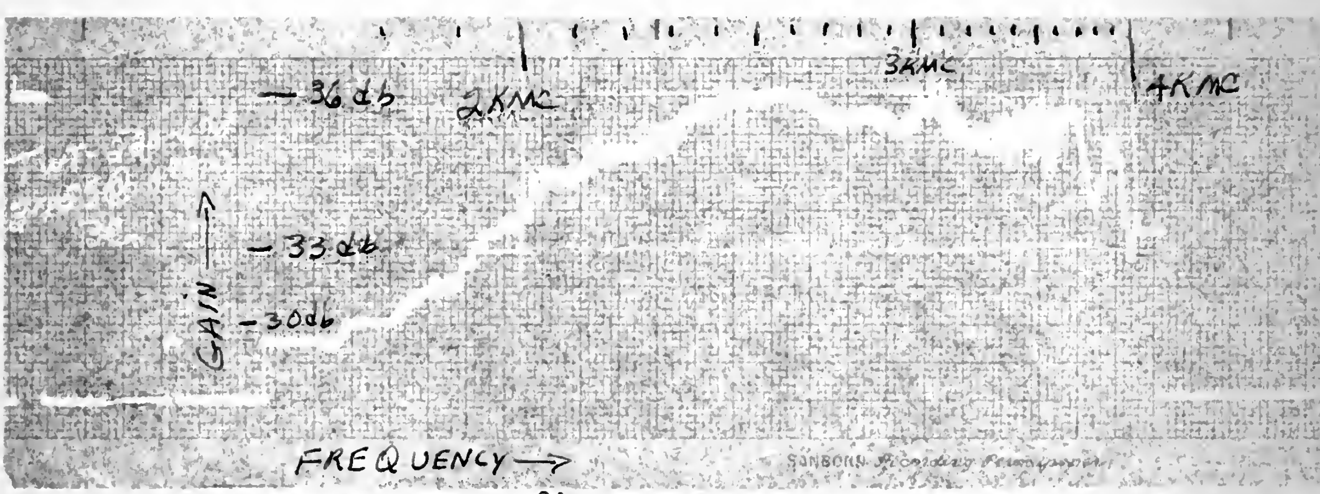


figure 9b

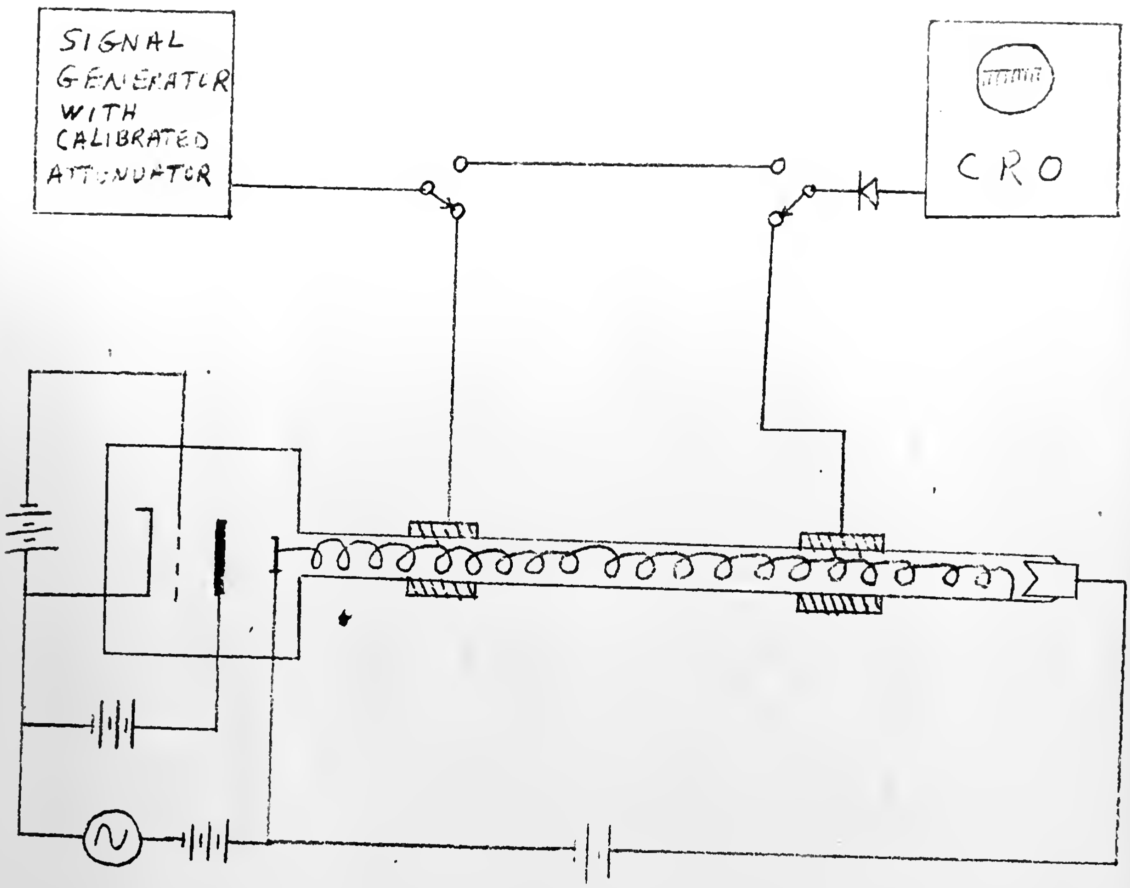


FIG. 10 SMALL SIGNAL GAIN MEASUREMENT SET UP

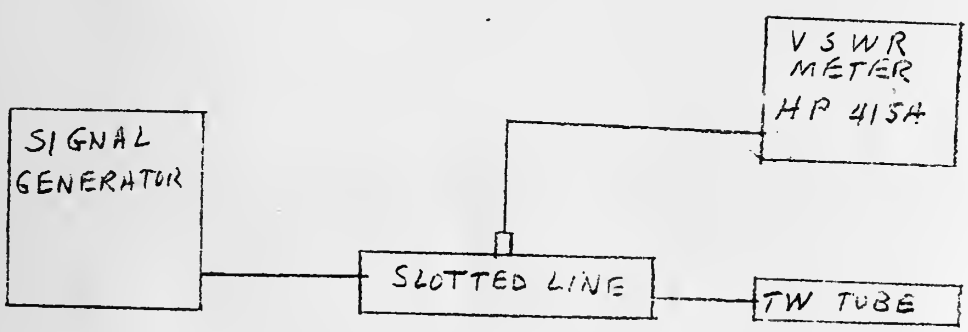


FIG. 11 VSWR MEASUREMENT SET UP

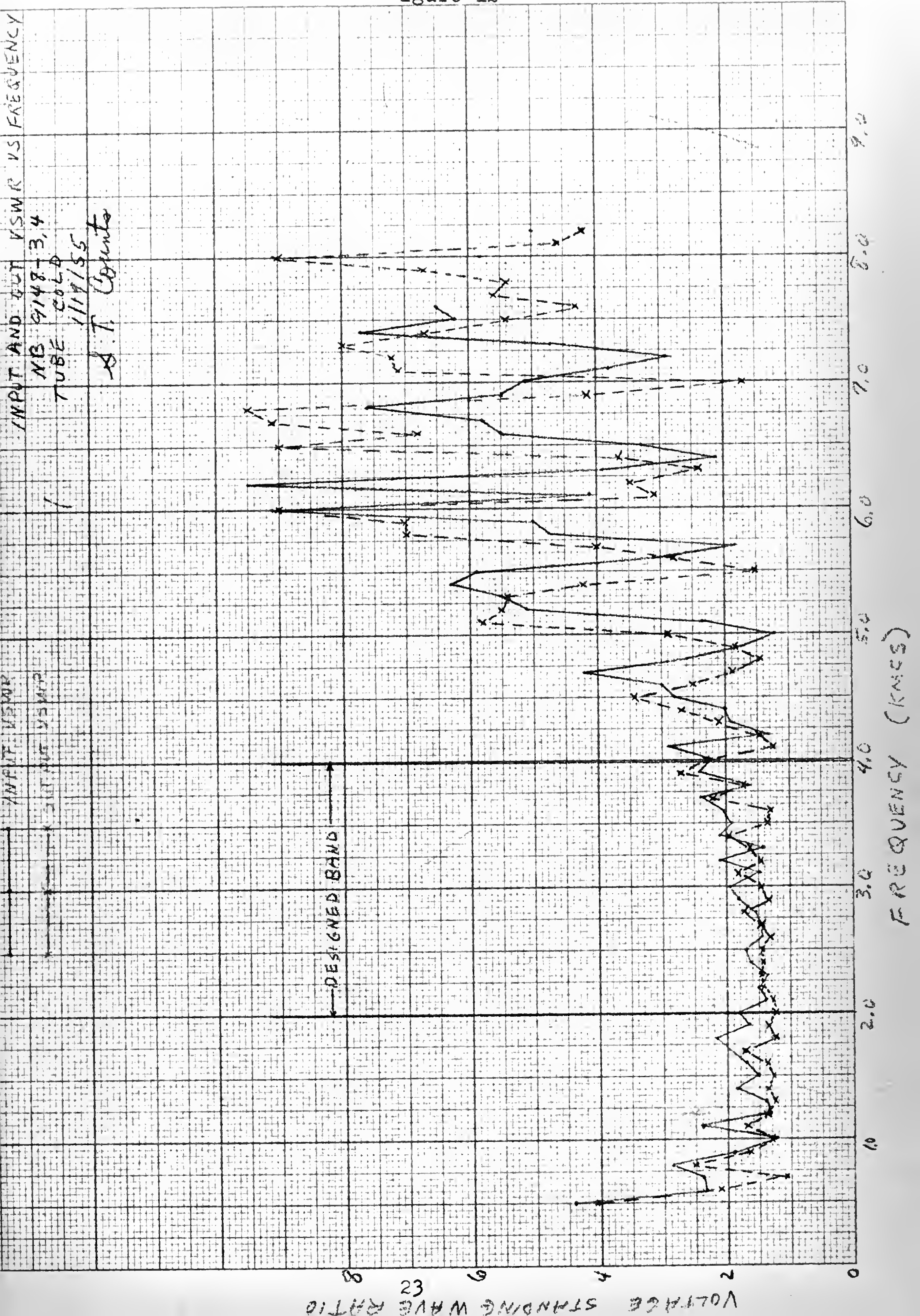
they should fit the glass envelope as closely as possible. The reason for this is to obtain the greatest value of coupling coefficient at the high end of the designed frequency band where the fields lie relatively close to the main helix. Even with this limitation the phase velocity can be optimized sufficiently by constructing the helical couplers with the proper turns per inch.

As an indication of impedance matching a measurement of voltage standing wave ratio is obtained. The usual engineering standard is that the voltage standing wave ratio shall not exceed two to one over the designed frequency range for both input and output couplers. This figure is not difficult to achieve over relatively wide bandwidths. An octave in frequency can be matched for a VSWR of less than two at frequencies up to ten kilomegacycles. The VSWR is measured with no beam present. The measurement set up used is shown schematically in figure 11. A plot of results obtained is shown in figure 12. The significance of the voltage standing wave ratio is that it gives an indication of the stability of the tube, the efficiency of the tube, and to some extent its probable performance in a system.

5. Cold loss or attenuation.

In the design of a traveling-wave tube there is a minimum amount of cold loss that must be present in order to achieve stability. For the amplifiers tested this figure was 50db. A schematic diagram of the measurement equip-

Figure 12



INPUT AND OUT VSWR VS FREQUENCY
N.B. 9148-3,4
TUBE COLD
1/17/55
INPUT VSWR
OUTPUT VSWR
DESIGNED BAND
FREQUENCY (KMCS)
VOLTAGE STANDING WAVE RATIO
0
2
4
6
8
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

ment used is shown in figure 19 and figure 13 shows a typical plot of attenuation versus frequency. The upper limit of attenuation measurement was at 4000 megacycles due to lack of suitable equipment.

Cold loss can be introduced in such a manner as to shape the gain of a traveling-wave amplifier within reasonable limits. A flat gain curve may be obtained to within plus or minus one decibel and shaped gains with desired slopes may be obtained by the proper control of attenuation. This is a difficult and tedious process at present as each tube must be treated individually.

6. Effect of control electrode.

The particular type of low level amplifier that this paper deals with has incorporated into the gun structure a grid or control electrode. This grid is used as a gating electrode, modulation electrode, or it need not be used at all. The control electrode functions in the same manner as a grid in conventional tubes by controlling the cathode current. A similar type of control may also be obtained by varying the anode voltage. Curves illustrating the effect on gain of each of these electrodes are shown in figures 14 and 15. Figure 16 gives a comparison of the effect on gain of each electrode.

7. Noise figure.

The average noise figure of the tubes tested ranged from 25 to 30 decibels (figure 17). This figure is higher

Figure 13

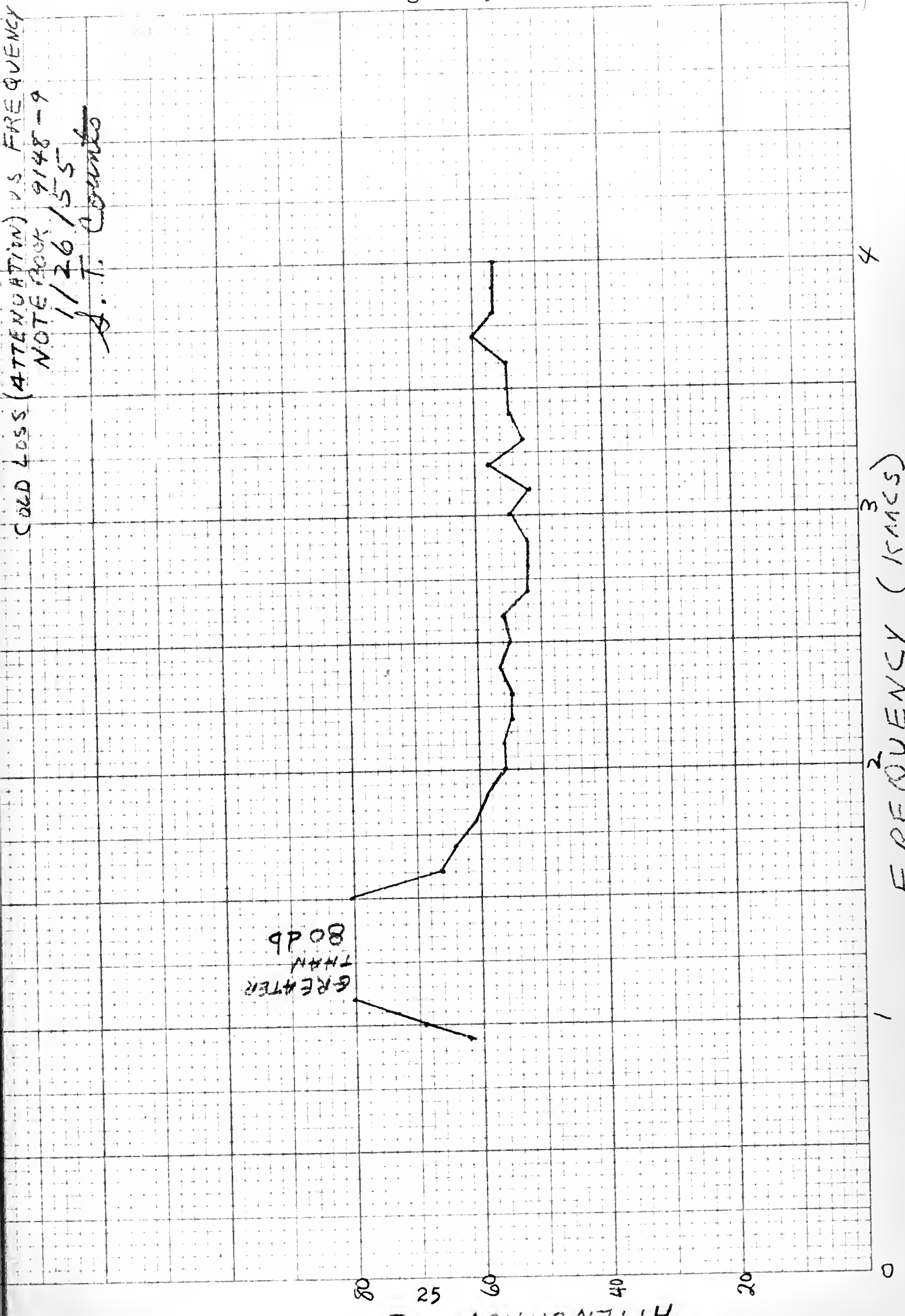

COLD LOSS (ATTENUATION) VS FREQUENCY
NOTEBOOK 9148-9
1/26/55
GREATER THAN 80db
FREQUENCY (KMC/S)
0
1
2
3
4
80
25
60
40
20

Figure 14

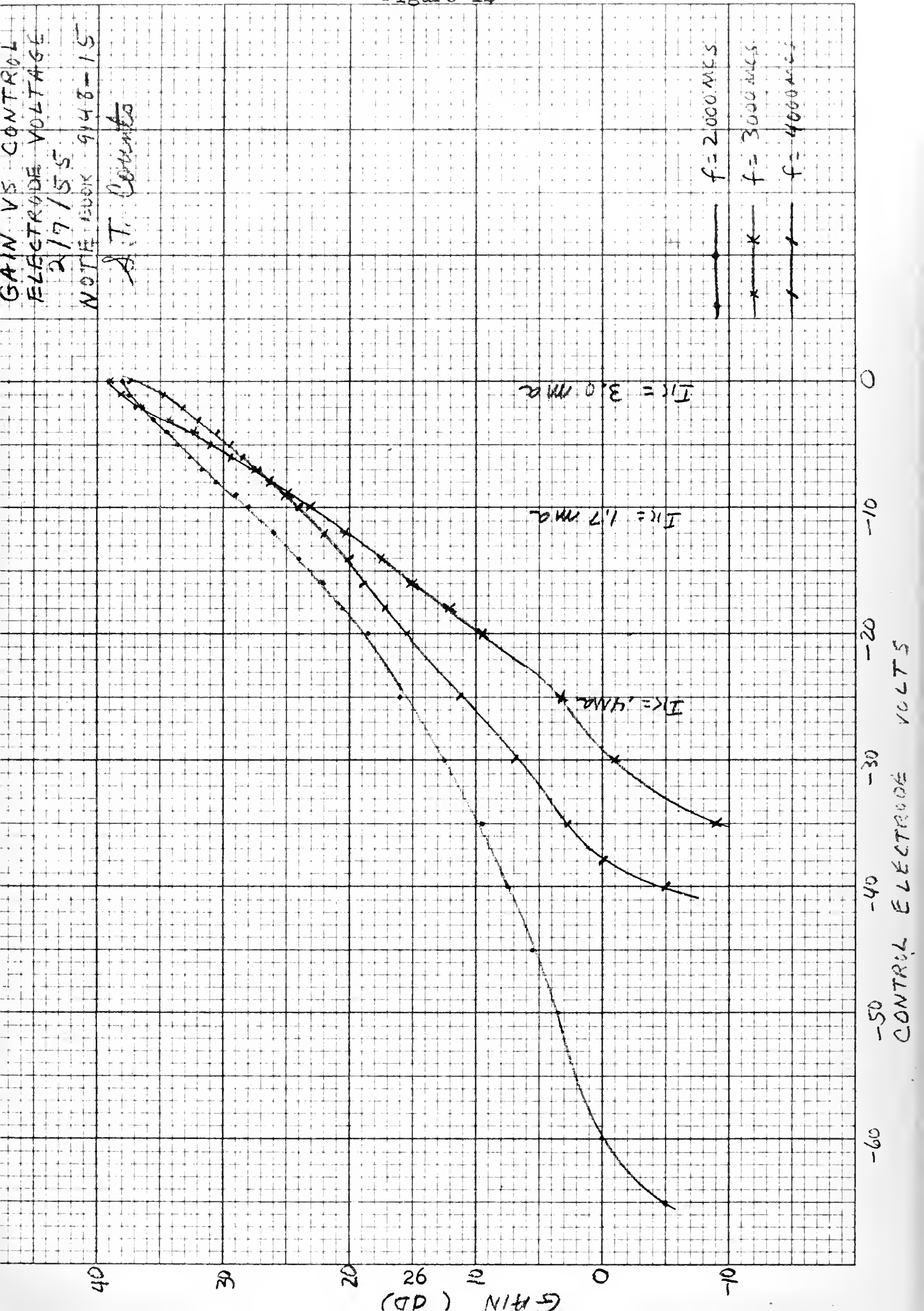

GAIN VS CONTROL ELECTRODE VOLTAGE
2/17/55
NOTE BOOK 9148-15
f = 2000 MCS
f = 3000 MCS
f = 4000 MCS
Ik = 3.0 ma
Ik = 1.7 ma
Ik = .4 ma
0
-10
-20
-30
-40
-50
-60
CONTROL ELECTRODE VOLTS
40
30
20
26
10
0
-10
GAIN (db)

Figure 15

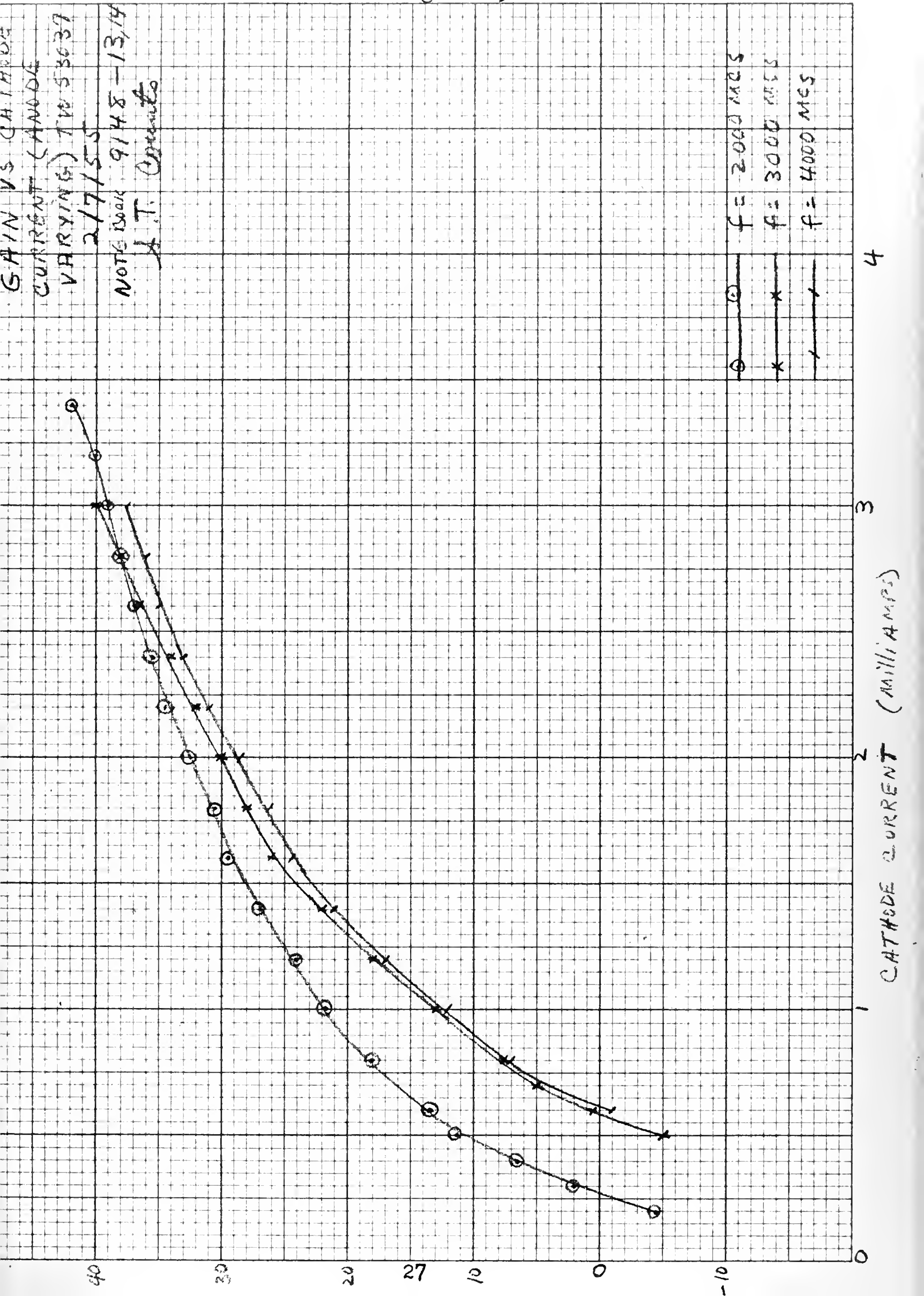
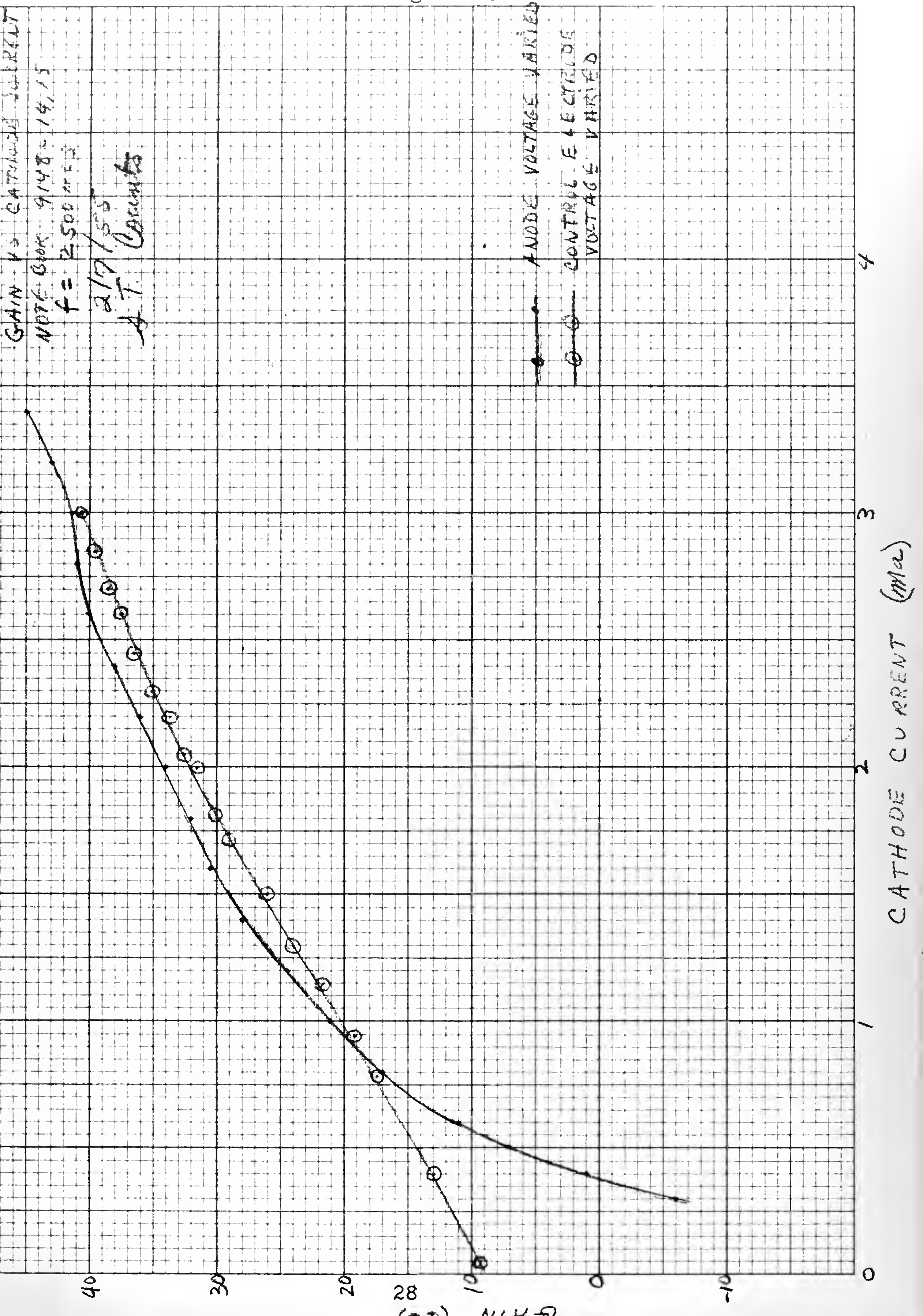

GAIN VS CATHODE
CURRENT (ANODE
VARYING) TW 53637
2/7/55
NOTE Book 9148-13,14
f = 2000 MCS
f = 3000 MCS
f = 4000 MCS
CATHODE CURRENT (MILLIAMPS)
0
1
2
3
4
40
30
20
10
0
-10

Figure 16

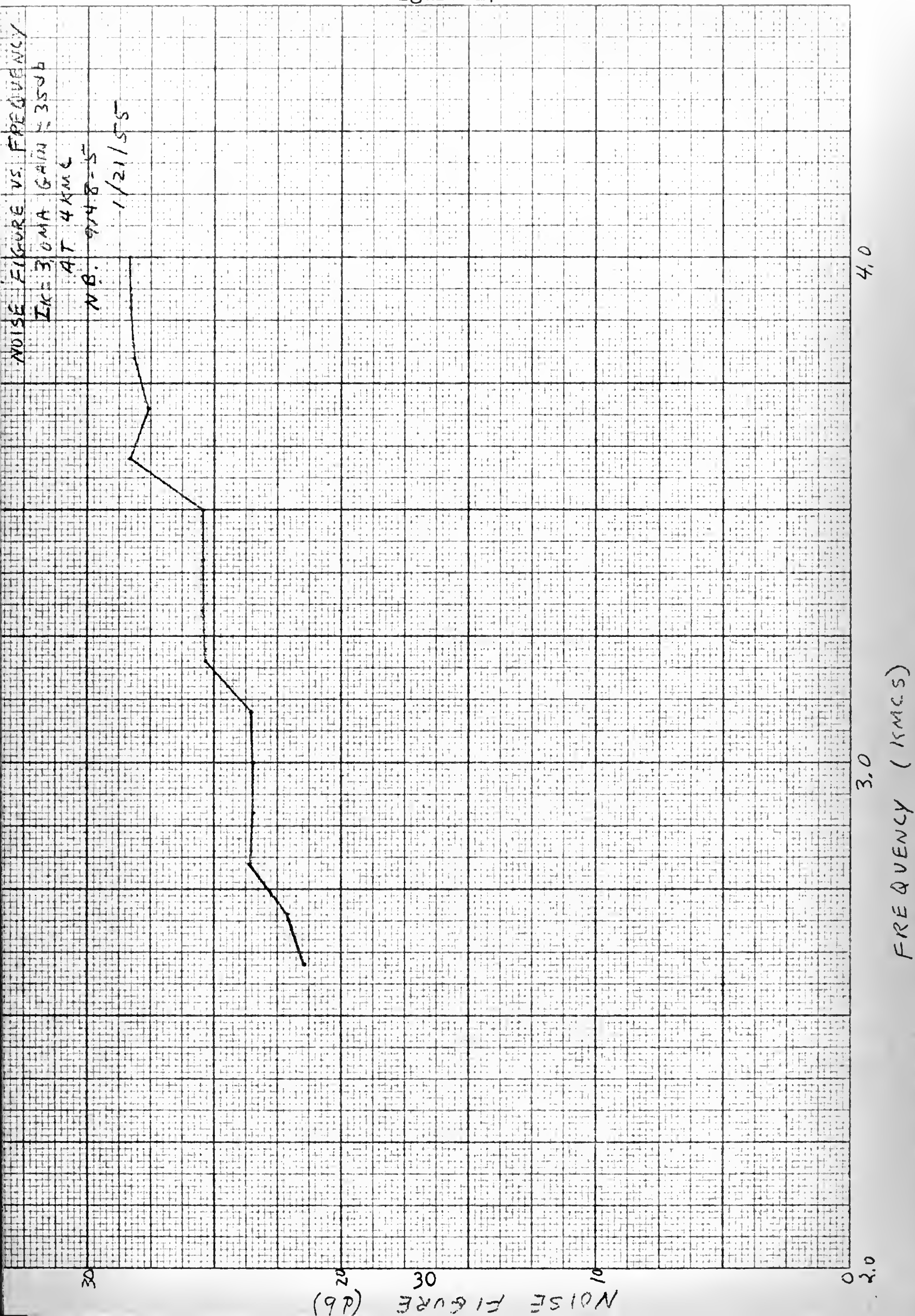

GAIN vs CATHODE CURRENT
NOTE BOOK 9148-14,15
f = 2500 mcs
ANODE VOLTAGE VARIED
CONTROL ELECTRODE VOLTAGE VARIED
CATHODE CURRENT (ma)
0
1
2
3
4
40
30
20
10
0
-10

than it should be for this type of traveling-wave tube. A primary factor in this higher noise figure is the configuration of the input portion of the helix. There is approximately an inch of helix between the electron gun and the input coupler that does not contribute to signal amplification, but does contribute to the noise generated. The noise figure could be reduced by decreasing this length and also by a gradual transition in the turns per inch of this portion of the helix. Another factor in the high noise figure is the amount of partition noise generated. Maximum gain is obtained when the beam is so focused that it scrapes the helix. Maximum interaction occurs but the partition noise is correspondingly increased. In the design of low noise traveling-wave amplifiers, the optimum condition is to have one-hundred percent transmission of the beam current leaving the cathode. This insures no electrode interception and electrode interception causes partition noise. In the amplifiers under discussion only forty percent of the cathode current reaches the collector with most of the current intercepted by the helix. Secondary emission also influences noise figure adversely [12].

8. Power measurements.

The performance of the traveling-wave amplifiers power wise was one of the most interesting phenomena observed. When the power level approaches saturation the performance can be predicted qualitatively, but very few concrete results

Figure 17


NOISE FIGURE VS. FREQUENCY
Ik = 3.0 MA GAIN ≈ 35 db
AT 4 KMC
N.B. 9748-5
1/21/55
FREQUENCY (KMCS)
2.0
3.0
4.0
NOISE FIGURE (db)
0
10
20
30

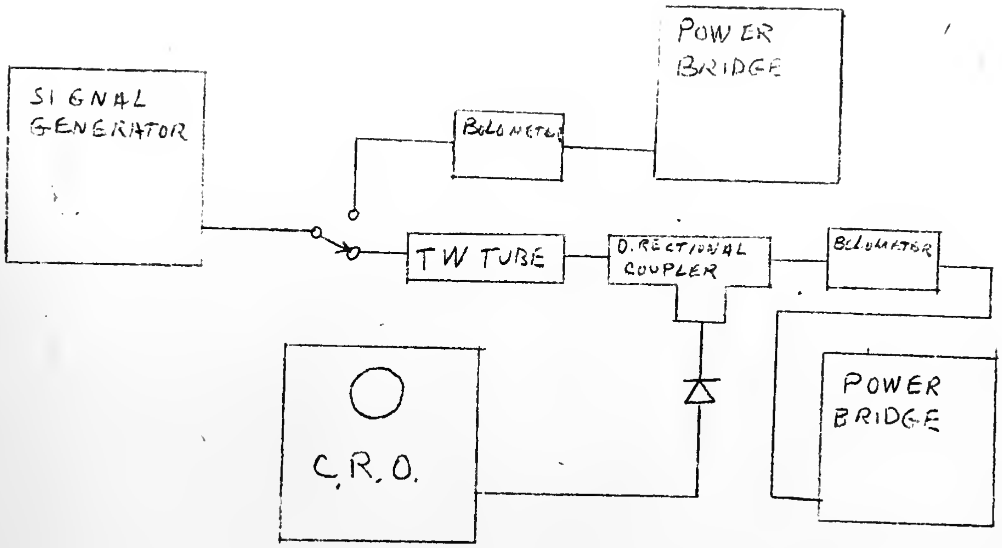


FIG. 18 SATURATION POWER MEASUREMENT SET UP.

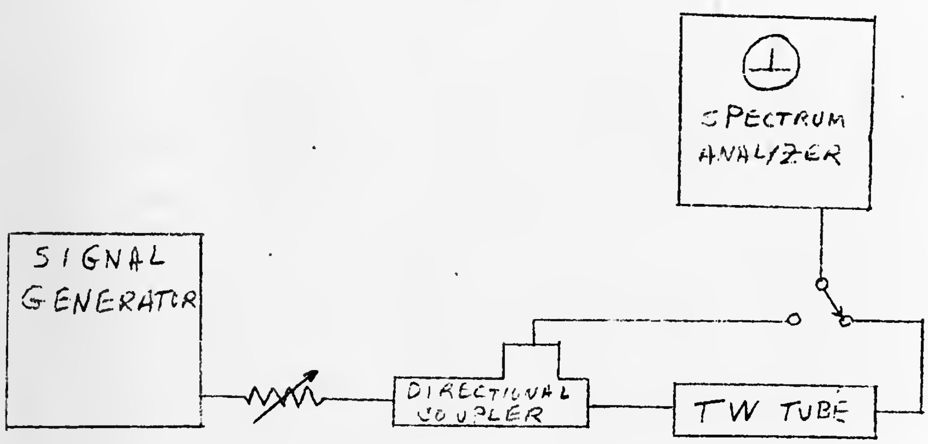


FIG. 19 ATTENUATION (COLD LOSS) MEASUREMENT SET UP.

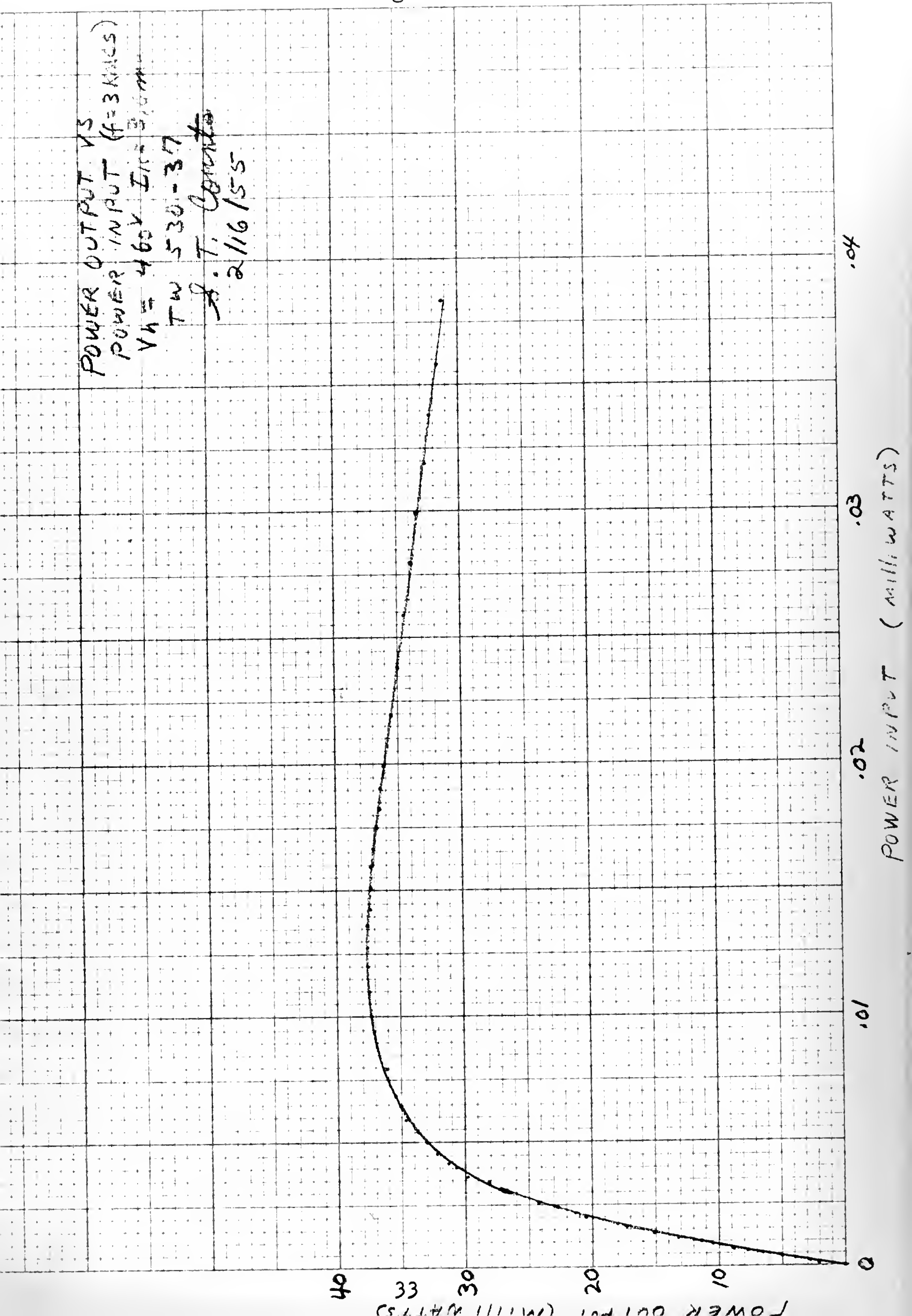
have been obtained by quantitative methods due to the non-linear behavior involved. The author attempted several power measurement tests. Some had rather surprising results.

The results of a measurement of power output versus power input are shown on figure 20. This curve is not complete. The input power was increased to as much as three milliwatts, but the output power was still dropping from the saturation valve. Driving sources were not available that would produce more than three milliwatts at the frequencies used. Saturation power occurs when the electron beam is at the optimum bunching condition. A further increase in input power causes the beam to be over bunched with a consequent decrease in output power. If the power input could have been increased further than three milliwatts, the output power would have reached a minimum and then would rise again. The secondary saturation power level is only slightly lower than the first one. This secondary saturation level occurs for the reason that the beam has again reached an optimum bunching condition. This process is known to repeat at least once more.[1]

A schematic diagram of the equipment used to measure saturation power is shown in figure 18. This measurement gave expected results at frequencies above 1800 megacycles (see figure 21). The saturation power output obtained was a maximum toward the middle of the designed frequency band and decreased on either side. Reducing the strength of the

1. Private conversation with Dr. S.F. Kaisel of Stanford University.

Figure 20


POWER OUTPUT VS
POWER INPUT (f=3 KMCS)
Vh = 460V
TW 530-37
2/16/55
POWER INPUT (MILLIWATTS)
0
.01
.02
.03
.04
10
20
30
33
40

focusing magnetic field or the cathode current decreased the power output. The input power required for saturation power output was a minimum in the designed band and rises at either end.

If the helix voltage is made synchronous at each frequency the power output can of course be maximized at each frequency. Considerable power outputs were obtained outside of the designed frequency range, especially at the low frequency end (see figure 22). In this region the normal broadband amplifier is dispersive and the tube is performing as a dispersive (voltage tunable) amplifier.

9. Harmonic generation.

Saturation power measurements in the octave below the minimum designed frequency gave a result that was, at first, not understood. The tube was adjusted for normal wide band operation. The helix voltage was made synchronous at 4000 megacycles, and the tube was focused in the magnetic field for maximum stable small signal gain. (The difference between the helix voltage required for maximum stable gain and maximum saturation power is small, on the order of five volts or less). When testing a particular tube, at a frequency between 1600 and 1800 megacycles, the saturation power would reach a minimum and then rise again, refer to figures 21 and 23. At first, this was thought to be due to the second harmonic content of the signal generator becoming appreciable as the fundamental driving power was increased.

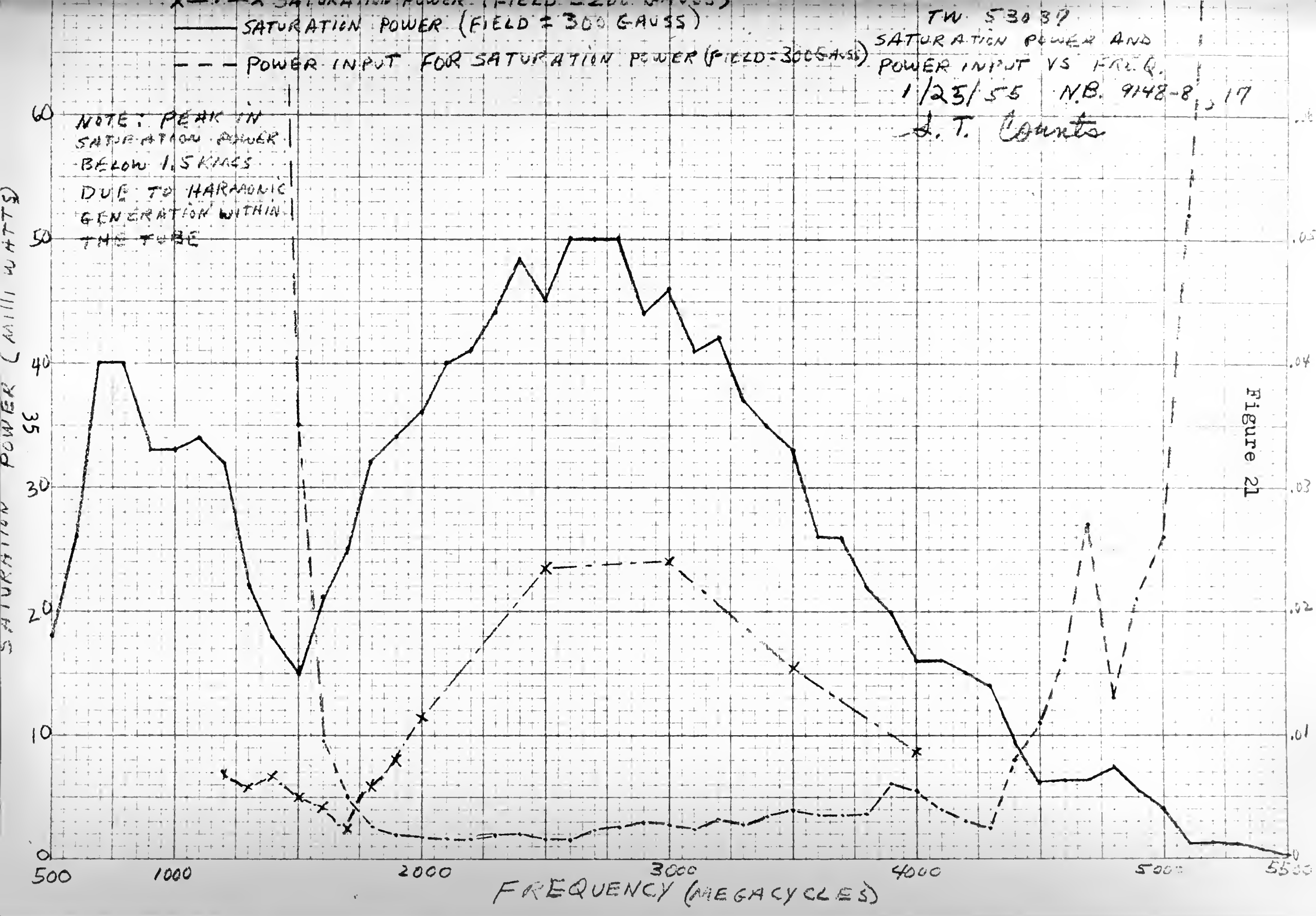

SATURATION POWER (FIELD = 300 GAUSS)
POWER INPUT FOR SATURATION POWER (FIELD = 300 GAUSS)
TW 53039
SATURATION POWER AND
POWER INPUT VS FREQ.
1/25/55 N.B. 9148-8, 17
J. T. Counts
NOTE: PEAK IN
SATURATION POWER
BELOW 1.5 KMCS
DUE TO HARMONIC
GENERATION WITHIN
THE TUBE
60
50
40
35
30
20
10
0
.01
.02
.03
.04
.05
500
1000
2000
3000
4000
5000
5500
FREQUENCY (MEGACYCLES)
SATURATION POWER (MILLI WATTS)

Figure 21

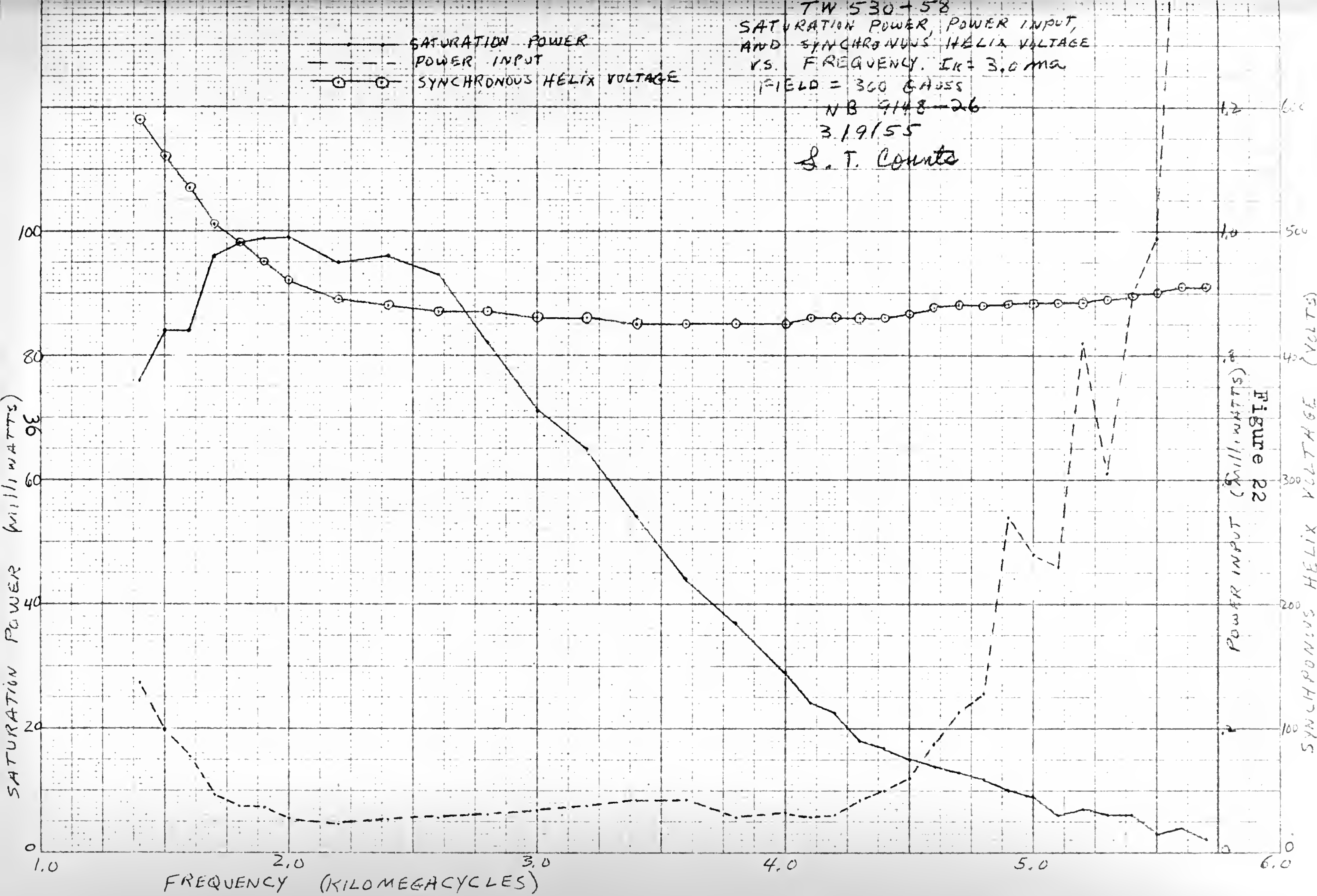
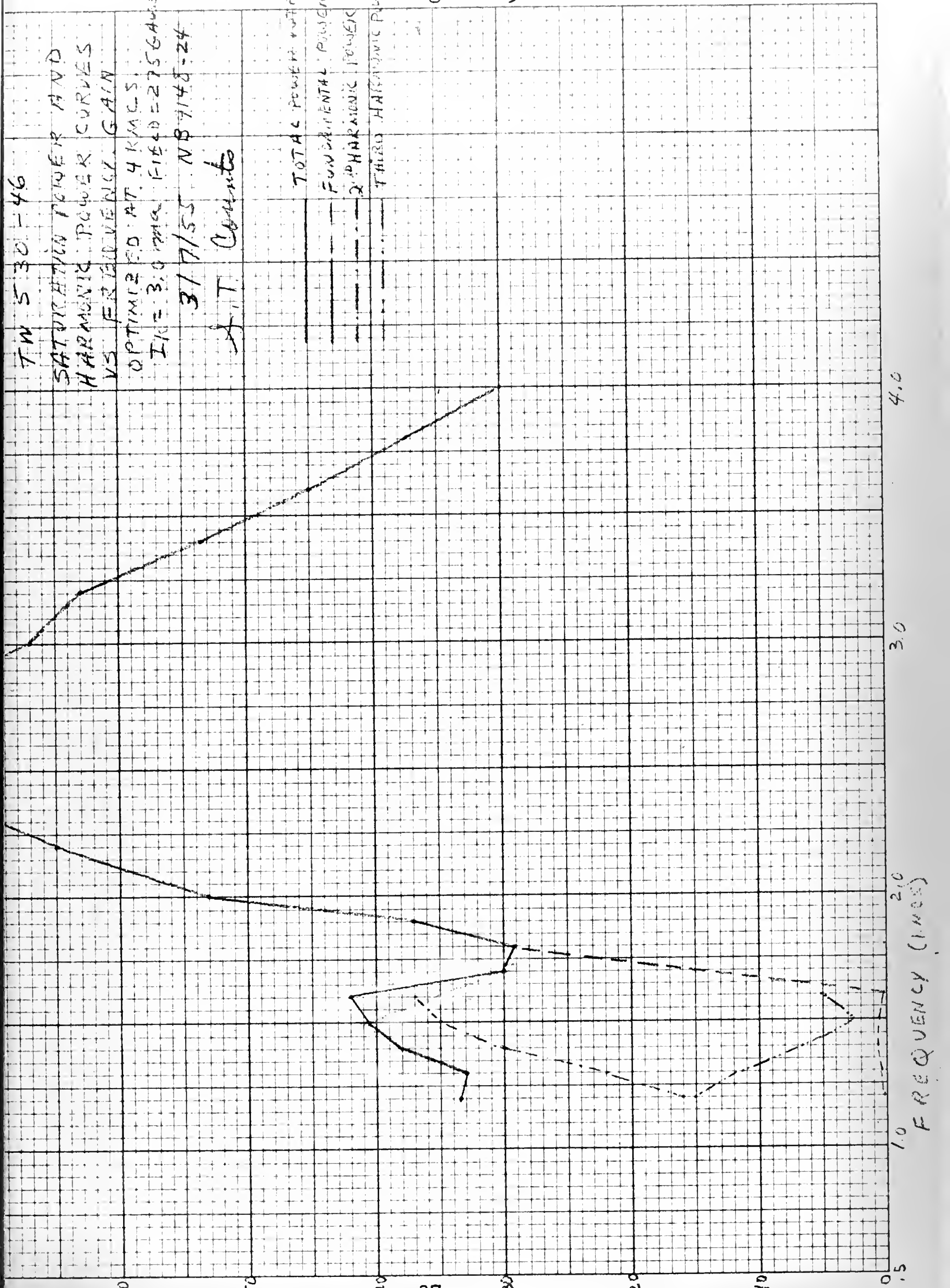

TW 530-58
SATURATION POWER, POWER INPUT, AND SYNCHRONOUS HELIX VOLTAGE VS. FREQUENCY. Ik = 3.0 ma
FIELD = 300 GAUSS
NB 9148-26
3/19/55
S. T. Counts
SATURATION POWER
POWER INPUT
SYNCHRONOUS HELIX VOLTAGE
SATURATION POWER (milliwatts)
0
20
40
60
80
100
POWER INPUT (milliwatts)
0
.2
.8
1.0
1.2
SYNCHRONOUS HELIX VOLTAGE (VOLTS)
0
100
200
300
400
500
600
1.0
2.0
3.0
4.0
5.0
6.0
FREQUENCY (KILOMEGACYCLES)

Figure 22

Figure 23


TW 5 30-46
SATURATION POWER AND
HARMONIC POWER CURVES
VS FREQUENCY, GAIN
OPTIMIZED AT 4 KMCS.
Ik = 3.0 ma FIELD = 275 GAUSS
3/7/55 NB 7148-24
TOTAL POWER
FUNDAMENTAL POWER
2ND HARMONIC POWER
THIRD HARMONIC POWER
0
10
20
30
40
50
60
.5
1.0
2.0
3.0
4.0
FREQUENCY
POWER (Milli WATTS)

The signal generators used were calibrated for the second and third harmonic power levels. These were found to be a minimum of minus 40 decibels with respect to the fundamental power level. As a further precaution a calibrated low pass filter was used at the output of the signal generator. These precautions insured the harmonic power level from the driving source to be a minimum of 90 decibels below the fundamental. After taking the above steps the phenomena of rising saturation power with decreasing frequency was still observed with no apparent change in magnitude. A precision wavemeter showed the output of the tube to contain the fundamental, first, second, third, fourth, etc. harmonic frequencies. By using band pass filters such as sections of wave guide, strip line, etc., the power level in each harmonic was measured in the instances where it could be isolated. The power level in each harmonic was dependent on its frequency i.e., whether or not it was in the designed bandwidth of the tube (figure 23). At a frequency of 1600 megacycles with the second harmonic at 3200 megacycles and the third at 4800, the second harmonic was predominant. As the driving frequency was decreased the second and third harmonics were both occurring in the designed frequency range and approximately equal power levels were obtained. In all instances the output power level of the fundamental was small, usually at unity gain or less. Also, small amounts of power could be found in the higher order harmonics,

but these were negligible in comparison to the amounts of power in the second and third harmonics.

The startling fact about this phenomena of harmonic generation is not that it occurs, but the amount of harmonic power obtained. It was much greater than expected. As an example of this, a given tube might deliver 50 milliwatts in the center of the designed band of from two to four kilo-megacycles. When driven by a frequencies between 700 and 1500 megacycles frequently delivered total harmonic powers of 40 milliwatts with power gains of from 13 to 20 decibels. The amount of signal drive varied from one-tenth to two milliwatts.

The fact that traveling-wave tubes will act a harmonic generators has been known for some time. Doehler [3], Putz [17], and others have reported on this. It is believed that most investigators have used driving frequencies in the non-dispersive region and the relative amounts of harmonic power obtained has been small under these conditions.

A qualitative explanation of the theory of harmonic generation is as follows. The synchronous helix voltage is such to give optimum wide band operation. When the driving frequency is below the minimum designed frequency the helix has a dispersive characteristic. This implies that the helix will not support the fundamental mode for the reason the helix voltage is non-synchronous at the driving frequency. In order to saturate the amplifier the signal dirve must be

increased. As the signal drive is increased a wave of sufficient amplitude is introduced on the helix to bunch the electron beam. This bunched beam is rich in harmonics. The lower order harmonics lie in the frequency range where the helix has significant impedance i.e., the designed band. The result is that field waves of adequate magnitude are induced to obtain high output power levels.

The desirable aspects of this phenomena are that a traveling-wave amplifier can be operated as a frequency multiplier or harmonic generator with power gain. Possible applications are in signal generators, microwave relays, and satellite television stations for remote areas.

CHAPTER V

SECONDARY EMISSION

1. Effects of secondary emission.

Secondary emission effects in traveling-wave amplifiers were investigated qualitatively. Quantitative measurements are difficult and require extreme care. The main problem is to isolate the effects of the secondary electrons.

An electron beam impinging on any known material will cause the emission of secondary electrons. The ultimate condition in traveling-wave tubes is to have the beam impinge 100 percent on the collector. The secondary electrons emitted by the collector are either recaptured or enter the interaction space. The electrons recaptured by the collector have been emitted with low velocities and present no problems. The high velocity secondary electrons have enough energy to enter the interaction region where they are focused by the strong magnetic field and travel down the tube toward the electron gun. The high velocity secondary electrons are composed for the most part of elastically reflected primary electrons and they leave the collector with essentially the same velocity as they arrived. Although the percentage of electrons reflected elastically is small (on the order of one percent or less), their effects are troublesome. It might be thought that electrons traveling in a direction opposite to the main beam would collide with the primary

electrons with consequent dissipation of energy. This is not the case, however, as the mean free paths involved make the possibility of a collision remote.

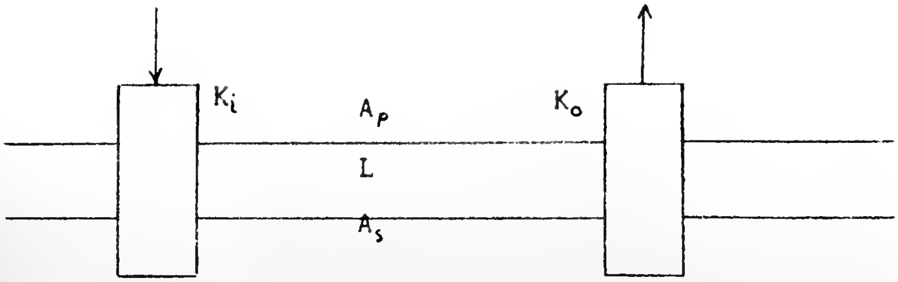
The first effect caused by secondary emission is an increase in the noise figure of the tube [12]. The randomly emitted high velocity secondary electrons interact with the reverse traveling fundamental mode and higher order forward and backward modes to contribute significantly to the noise level in the tube. Peter and Ruetz [12] have performed several quantitative measurements of this phenomena on low noise traveling-wave amplifiers. Their work is at present the only authoritative one on this subject.

A second effect is tube instability caused by regeneration due to secondary emission. Instability occurs in the following manner. With the tube operated as an amplifier the magnitude of the field wave is large at the output coupler. A portion of this field wave is reflected by the output coupler and another portion from the collector end of the helix. The primary beam of electrons striking the collector has had a small fraction undergo elastic reflection. The reflected electrons return to the interaction space with the same velocity as when they left and thus are in synchronism with the reflected field waves. Interaction and hence amplification occurs in a backward direction. After reaching the attenuator and/or input coupler a portion of the amplified reflected wave is again reflected. The

fraction of the wave that has undergone this second reflection interacts with the primary beam and is also amplified. Oscillation will occur if the gain of the feedback loop is greater than unity, refer to figure 24. This brief explanation has been greatly simplified. Factors neglected have been interaction with higher modes, secondary emission as a result of helix interception, etc.

2. Methods of minimizing secondary emission effects.

The adverse effects of secondary emission may be minimized by following measures. First, and probably the most effective is the design of the collector. A collector should have a long sleeve, whose depth is at least three times the maximum beam diameter, followed by a tapered section. The angle of this tapered section should not exceed thirty degrees. Second,the collector material should have a low secondary to primary electron ratio. Third, the inside of the collector can be coated with materials such as carbon black, soot, or aquadag that have low secondary to primary ratios. Fourth, a field interrupter (field spreader) can be used to reduce the number of secondary electrons reaching the interaction region. A field interrupter is a piece of magnetic material placed outside of the collector that distorts the magnetic field. The magnetic field is distorted in a manner to make the primary beam hit the side walls of the collector. Since the reflected electrons obey Bragg's Law[1] it is hoped that they will dissipate their energy



$A_p^2 A_s K_o K_i L = 1$ For oscillation

A_p - Forward gain (primary beam)

A_s - Gain in backward direction due to secondary electron beam

K_o - Reflection coefficient output coupler

K_i - Reflection coefficient input coupler

L _ Loss in backward direction due to external attenuator

Figure 24

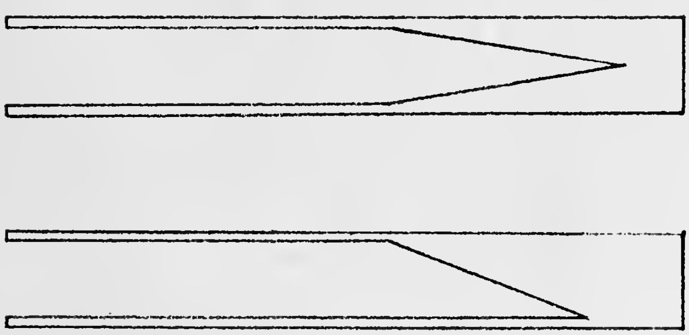


Figure 25 Collector configurations

in multiple collisions with the collector walls. The technique usually used to overcome the effects of secondary emission is to design the collector properly and then use a field interrupter. Figure 25 illustrates effective collector designs.

3. Qualitative measurements.

An investigation was made of the effect on noise figure of increased interception current. The results are shown below.

Run	1	2
Beam Current	4ma	4ma
Helix interception current	10μa	20μa
Anode interception current	7μa	17μa
Percent transmission	99.575	99.075
Noise figure	18 db	25 db

In run 1 the tube was adjusted for optimum noise figure at a frequency of three kilomegacycles. In run 2 the field interrupter was moved slightly to increase electron reflection. A small increase in secondary emission can ruin the noise figure of a tube as shown above. The data is qualitative in the sense that the increase in noise figure due to secondary emission effects and that due to increased interception as a result of defocussing cannot be separated. The defocussing should not have contributed significantly.

The stability of the tubes can be investigated by the equipment used to measure small signal gain (figure 10).

A 60 cycle source is placed in series with the helix d.c. power supply. This sweeps the helix voltage at a 60 cycle rate. Sweeping the helix voltage causes the gain curve to have a peak. When oscillation occurs the base line will break and a spike will appear. The amplitude of the spike indicates the level of oscillation. By changing the position of the tube in the magnet it is usually possible to eliminate oscillation. This defocussing of the electron beam usually reduces the amount of interaction and hence gain and power output.

The oscillation frequencies known to be due to secondary emission were found from 2100 to 5500 megacycles with each tube unlike any other.

CHAPTER VI

CONCLUSIONS

Traveling-wave tubes have now reached a state of development that they are becoming available on the commercial market. They are being utilized for several military applications in the microwave region. Their present uses in the commercial field are in microwave relays and in broadband amplifiers for laboratory purposes.

Although the traveling-wave tube shows great future promise, there are still a large number of problems to be solved. Some of these are: The tubes must be stable under all conditions of input and output loading. They must be made more rugged so they will function under conditions of vibration and shock. This especially applies to the method of supporting the helix inside the envelope. The magnet can be improved. The solenoids presently used should be made smaller and lighter. Periodic and permanent magnet focusing should be investigated further. It is believed the overall length of the helix can be reduced without significant loss in gain. A method of introducing uniform attenuation is needed. The coupling devices, adequate at present, should be broadbanded even more as the usable bandwidth of the tube is limited by the bandwidth of the couplers. Efforts are being made to solve all of these problems and with time the solutions will be obtained.

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[illegible]

APPENDIX A[1]

DERIVATION OF EXPRESSION FOR BEAM CURRENT

A convenient expression for the a-c current induced by an electric field of fairly arbitrary characteristics is given by Pierce and Shepherd in their article on reflex klystrons[2] as due to Petrie, Strachey, and Wallis. The expression is derived there.

$$i(z) = -\frac{j I_o}{2 V_o} \int_o^z E(\xi)\, \beta_e (z-\xi)\, \epsilon^{-j\beta_e (z-\xi)}\, d\xi$$

where

I_o = d-c beam current

V_o = d-c beam voltage

$\beta_e = \frac{\omega}{u_o}$

$\omega = 2\pi f$

u_o = d-c beam velocity

ξ = running variable of distance

$E(\xi)$ = electric field given as a function of ξ.

Here intergration is carried out from $\xi = o$ to $\xi = z$ which is the interval in which field exists.

For the case in which the applied field is of constant amplitude and propagating in the same direction as the direction of electron travel,

$$E(\xi) = E_o \epsilon^{-j\beta\xi}$$

where

$B = \frac{\omega}{v}$

v = phase velocity of wave

1. Appendices A,B, and C are taken in their entirety from 4
2. J.R. Pierce and W.G. Shepherd, "Reflex oscillators," Bell Syst. Tech. J., 26: 460-681 (1947), esp. pp. 663 ff.

[illegible]

In this case the current at z is given by:

$$i(z) = -\frac{jI_0}{2V_0}\int_0^z E_0 \epsilon^{-j\beta\xi} \epsilon^{-j\beta_e(z-\xi)} \beta_e (z-\xi)\, d\xi$$

$$= -\frac{jI_0}{2V_0} E_0 \epsilon^{-j\beta_e z} \beta_e \int_0^z \epsilon^{-j\theta\xi} (z-\xi)\, d\xi$$

where

$$\theta = \beta - \beta_e$$

$$i(z) = -\frac{jI_0}{2V_0} E_0 \epsilon^{-j\beta_e z} \beta_e \left[\frac{z}{j\theta} - \frac{1}{\theta^2}(\epsilon^{-j\theta z} - 1)\right]$$

For θ approaching 0, i.e., beam and field in synchronism,

$$i(z) \cong -\frac{jI_0}{2V_0} E_0 \epsilon^{-j\beta_e z} \beta_e \left[\frac{z}{j\theta} - \frac{1}{\theta^2}\left(1 - j\theta z + \frac{(j\theta z)^2}{2} - 1\right)\right]$$

$$i(z) = -\frac{jI_0}{2V_0} E_0 \epsilon^{-j\beta_e z} \beta_e \left[-\frac{(j\theta z)^2}{2\theta^2}\right]$$

$$i(z) = -\frac{jI_0}{4V_0} E_0 \beta_e z^2 \epsilon^{-j\beta_e z}$$

which is a current growing as the square of distance traveled in the presence of the field. This expression is valid for small signals only, since the original expression for current was derived on this basis.

[illegible]

[illegible]

[illegible]

APPENDIX B

DERIVATION OF EXPRESSION FOR TOTAL INDUCED ELECTRIC FIELD

If an a-c current travels near a uniform transmission line in a region in which a field would exist if power were being supplied to the transmission line, the current will induce a field on the line.[1] This field is the sum of infinitesimal wavelets induced at each point along the line. Consider a current element of length $d\xi$, having a current $i(\xi)$. This current will induce a field wavelet on the line traveling to the left and an equal wavelet traveling to the right. These two wavelets represent power flow to the left and to the right.

Now, the field at the beam for a given power flow on the circuit in the absence of the beam may be calculated for any given circuit, given the field distribution. A standard form used to express this quantity has the dimensions of impedance. It is normally called the impedance of the circuit, but is an impedance quite different from the usual characteristic impedance of the circuit:

Circuit impedance $= K = \dfrac{E^2}{2\beta^2 P}$

where

E = axial electric field <u>at the position of the beam</u>

B = $\dfrac{\omega}{v}$

P = power transmitted across any plane perpendicular to the direction of power flow, for a field E to exist at the

1. This derivation follows those given by J. Bernier, "Essai de theorie du tube electronique a propagation d'onde," Ann. Radio elect., 2:87-101 (1947): and J.R. Pierce, "Theory of the beam-type traveling-wave tube," Proc. I.R.E., 35:111-123 (1947)

position of the beam.

To produce a field dE at the beam requires a power

$$dP = \frac{(dE)^2}{2\beta^2 K} = \frac{dE \cdot dE^*}{2\beta^2 K}$$

The total power flowing into the circuit from a current element, in terms of the field induced at the position of the beam dE, is

$$dP = -\frac{i(\xi)\, d\xi\, dE^*}{2}$$

This expression is negative because of our sign convention for field. The factor of two results from using peak values of field and current, and the product of current and length times field simply represents the power flow to the field from a current flowing against a potential gradient in a distance d.

The power flowing in either direction is one half of the above:

$$dP = -\frac{i(\xi)\, d\xi\, dE^*}{4}$$

The field (at the beam position) that travels in either direction is then

$$dE = \frac{2\beta^2 K\, dP}{dE^*} = -\frac{i(\xi)\, d\xi\, K\beta^2}{2}$$

An integration may be performed to obtain the total field at any value of z, for the case of an interaction space extending from 0 to L. The following equation represents the total induced field. If an applied field is present it must be added to the expression below to obtain the total field.

$$E(z) = -\frac{K\beta^2}{2}\left\{\int_0^z i(\xi)\, \epsilon^{-j\beta(z-\xi)}\, d\xi + \int_z^L i(\xi)\, \epsilon^{j\beta(z-\xi)}\, d\xi\right\}$$

Here an addition is made of all induced field wavelets propagating in a forward direction on the circuit (as $e^{-j\beta\xi}$) that are induced between 0 and z. The field dE at ξ is multiplied by $e^{-j\beta(z-\xi)}$, to take into account the phase change that will occur in traveling along the circuit from ξ to z. The second integral is an addition of all wavelets propagating in a backward direction as $e^{j\beta\xi}$ that are induced between z and L. Again the field at ξ is multiplied by a phase factor, here $e^{j\beta(z-\xi)}$, to include the phase change from ξ to z along the circuit.

The above equation is, of course, for a circuit with phase and group velocities in the same direction.

APPENDIX C

DERIVATION OF EXPRESSION FOR TOTAL ELECTRIC FIELD IN CLOSED FORM

Using the results of Appendices A and B, it is quite simple to derive the series representation for field vs distance in the traveling-wave amplifier.

First, assume a constant-amplitude applied field:

$$E_1 = E_0 \epsilon^{-j\beta z}$$

The a-c current induced by this field, for synchronous beam and circuit velocities is, from Appendix A:

$$i_1 = -\frac{jI_0}{4V_0}\beta z^2 E_1$$

This current induces a secondary field wave that may be calculated from Appendix B, neglecting the contribution from the backward-wave integral:

$$E_2 = -\frac{K\beta^2}{2}\left(-\frac{jI_0}{4V_0}\beta E_0\right)\int_0^z \epsilon^{-j\beta\xi}\epsilon^{-j\beta(z-\xi)}\,d\xi$$

$$= j\left(\frac{KI_0}{4V_0}\right)\frac{\beta^3 E_0 \epsilon^{-j\beta z}}{2}\left[\frac{z^3}{3}\right]$$

Let

$$C^3 = \frac{KI_0}{4V_0}$$

Then

$$E_2 = -(-j)\frac{(\beta C z)^3}{3!}E_1$$

The secondary current wave can be calculated from the equation in Appendix A:

$$i_2 = -\frac{jI_0}{2V_0}\left[-(-j)E_0\frac{\beta^3 C^3}{3!}\right]\int_0^z \xi^3\beta(z-\xi)\epsilon^{-j\beta\xi}\epsilon^{-j\beta(z-\xi)}\,d\xi$$

[illegible]

$$[illegible]$$

$$[illegible]$$

$$[illegible]$$

$$[illegible]$$

$$i_2 = -(-j)^2 \frac{I_0 E_0}{2 V_0}\left(\frac{\beta^3 C^3}{3!}\right) \beta_e \epsilon^{-j\beta z}\left[\frac{z^4}{4} - \frac{z^5}{5}\right]$$

$$= -(-j)^2 \frac{I_0}{2V_0}\left(\frac{1}{\beta C^2}\right) \frac{(\beta C z)^5}{5!} E_1$$

The tertiary field is given by

$$E_3 = -\frac{K\beta^2}{2}\left[-(-j)^2 \frac{I_0 E_0}{2 V_0}\left(\frac{\beta^5 C^5}{\beta C^2}\right)\frac{1}{5!}\right]\int_0^z \xi^5 \epsilon^{-j\beta\xi} \epsilon^{-j\beta(z-\xi)} d\xi$$

$$= (-j)^2 \frac{K I_0}{4 V_0} E_1 \left(\frac{\beta^6 C^5}{C^2}\right)\frac{1}{5!}\left(\frac{z^6}{6}\right)$$

$$= (-j)^2 \frac{(\beta C z)^6}{6!} E_1$$

Then the series may be written as

$$E = E_1\left[1 - (-j)\frac{(\beta C z)^3}{3!} + (-j)^2 \frac{(\beta C z)^6}{6!} - \cdots\right]$$

$$= E_1 \sum_{n=0}^{\infty} (-1)^n (-j)^n \frac{(\beta C z)^{3n}}{(3n)!}$$

APPENDIX D

R.E.T.M.A. CHARACTERISTICS FOR WIDE BAND TRAVELING-WAVE AMPLIFIER 6493

The R.E.T.M.A. ratings are as shown.

Electrical Ratings, Absolute Values

1.	Heater Voltage	6.3 ± 10%
2.	Heater Current	1.0 amps
3.	Maximum Gating Electrode Voltage	-100 to +15
4.	Maximum First anode Voltage	+600
5.	Maximum Helix Voltage	+750
6.	Maximum Helix Current	2.0 ma.
7.	Maximum Collector Voltage	+750^{V} D.C
8.	Maximum Collector Dissipation	1.5 watts
9.	Maximum helix Voltage to ground	+750

All voltages are with respect to the cathode unless otherwise specified.

Electrical Information

10.	Maximum frequency	4100 MCS
11.	Minimum frequency	1900 MCS
12.	Minimum Cold Transmission loss	50 db

Mechanical Information

13.	Type of Cathode	Unipotential oxide
14.	Base	Octal plug
15.	Type of envelope	Metal capsule
16.	Magnetic Field Strength	400 gauss

17.	Length of Magnetic Field	14" uniform
18.	Mounting position	any
19.	Weight-tube & Capsule only	less than 2 lbs.
20.	R.F. Input and output impedance and Type Conductor	50 ohms BNC coaxial
21.	Type of Cooling	Convection air
22.	Maximum Collector Temperature	200°C

<u>Typical Operation</u>

23.	Center frequency	3 KMCS
24.	Gating Electrode Voltage	0 (-70 for cutoff)
25.	First Anode Voltage	+350
26.	First Anode Current	less than 500μa
27.	Helix Voltage	+400
28.	Helix Current	500μa
29.	Collector Voltage	+550
30.	Collector Current	2.5 ma
31.	Power output	15 milliwatts
32.	Small Signal Gain	greater than 35db
33.	Operating band to 3 db power points	2.1-3.9 KMCS
34.	Noise Figure at Operating Band	less than 25 db